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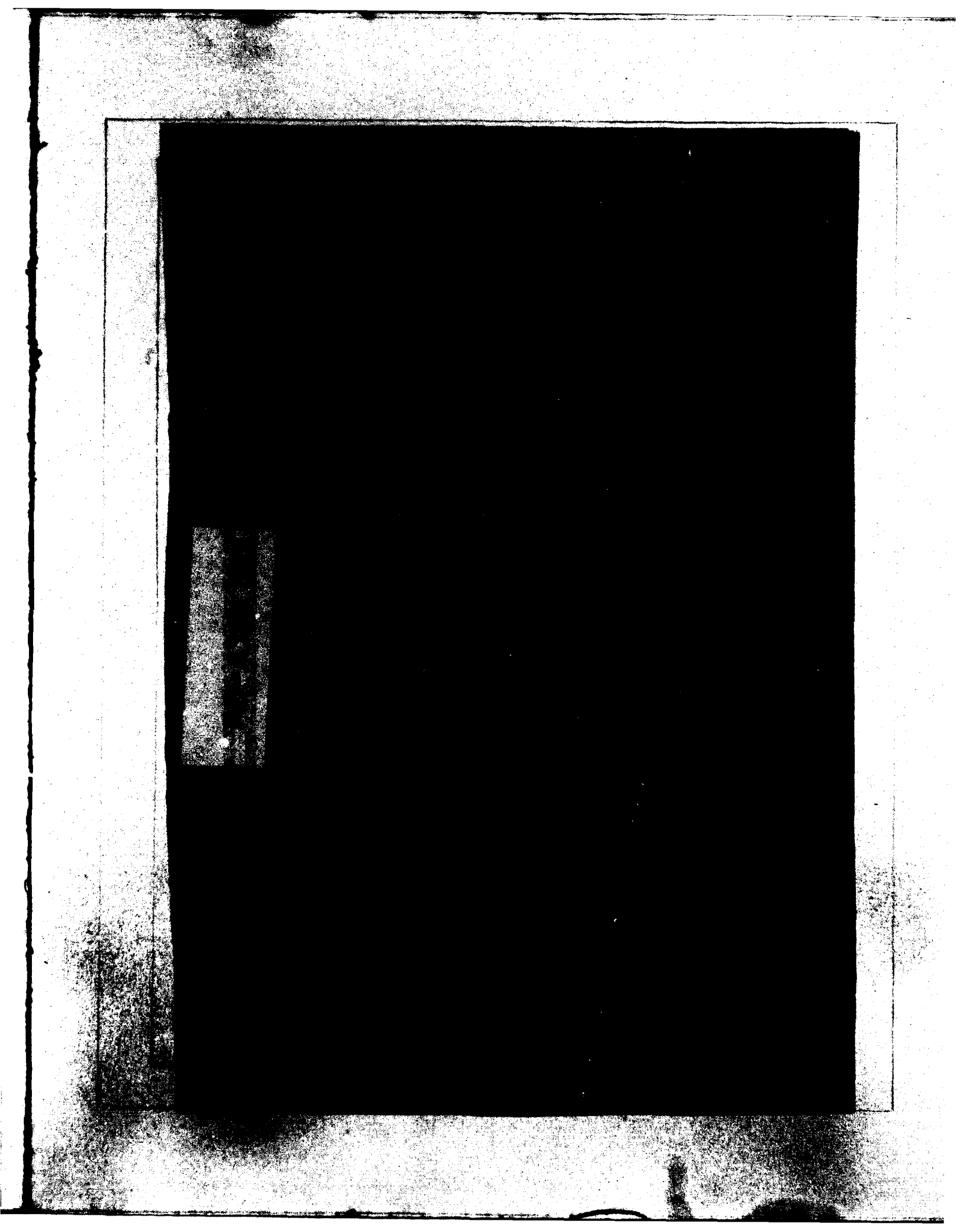
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**NORTH ATLANTIC TREATY ORGANIZATION**  
**ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT**  
**(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)**

**AGARDograph No. 304**  
**STANDARD FATIGUE TEST SPECIMENS**  
**FOR FASTENER EVALUATION**

by

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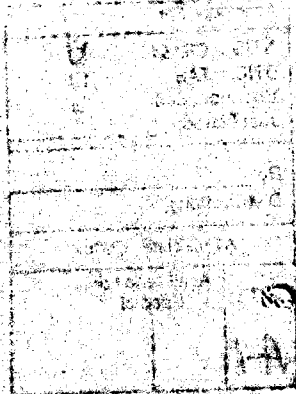
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## PREFACE

Aircraft fatigue is a very expensive phenomenon in terms of inspection, of maintenance and repair and of decreased aircraft availability. Hence, design for good fatigue performance remains of great importance. Mechanically fastened joints quite often turn out to be the fatigue critical elements in aircraft structures. Recently, an extensive co-operative programme coordinated by the AGARD Structures and Materials Panel was completed in which the fatigue performance of a wide range of fastener systems were evaluated.

During this programme, which also used a variety of specimen configurations, the desirability of a limited number of standard specimens to facilitate fastener evaluation in the future, became apparent. Hence, the Structures and Materials Panel decided to set up a Working Group that would try to define a limited number of recommended specimen configurations, on the basis of a co-operative test programme.

This programme, which was very ably co-ordinated by Mr. R. Cook of the Royal Aircraft Establishment has now been successfully completed and the present report contains the results of this collaborative effort.

J.B. de Jonge  
Chairman, Working Group on Standard  
Fatigue Test Specimens for Fastener Evaluation

## SUMMARY

An AGARD-coordinated programme which examines the fatigue performance and joint characteristics of a number of mechanically fastened joints has been completed. This report describes the programme which examines mechanically fastened joints with 1) no or low secondary bending and 2) with high secondary bending. In part 1, three types of joint are assessed which exhibit no, low and high amounts of load transfer by the fastener. The no load transfer joint was rejected and the low and high load transfer joints were considered to be equivalent in rating fastener systems. In part 2, three types of single shear joint are considered. They are compared on the basis of load transfer and secondary bending characteristics and also on the fatigue endurance with a range of fastener systems installed. Only one joint, the UK designed Q-joint, adequately fulfilled the requirements of a standard joint for fastener evaluation purposes.

L'AGARD ("Advisory Group for Aerospace Research and Development" - groupe consultatif pour la recherche et les réalisations aérospatiales) a mené à bien un programme coordonné d'examen des performances en fatigue et des caractéristiques de solidité de toute une série de liaisons par fixation mécanique.

Le présent exposé décrit le programme qui traite des jonctions mécanique présentant

- (1) une manifestation faible ou nulle de flexion secondaire,
- (2) une flexion secondaire importante.

Dans la première partie, on examine trois types de liaison qui révèlent un niveau de transfert de charge par la fixation respectivement nul, faible et élevé. On a écarté la solution d'une liaison sans aucun transfert de charge et estimé qu'un transfert de charge faible ou élevé constituait un bon équivalent pour l'évaluation des systèmes de fixation. Dans la deuxième partie, on traite trois types de liaison à cisaillement simple. On les compare entre eux en étudiant le transfert de charge et les caractéristiques en flexion ainsi que la résistance à la fatigue d'une série de dispositifs de fixation posée. Un seul système, le modèle à pression dynamique conçu par les Britanniques, a satisfait convenablement aux conditions imposées à un assemblage courant destiné à l'évaluation des fixations.

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## 1 INTRODUCTION

The most common site of fatigue crack initiation in aircraft structures is from a fastener hole. In consequence there have emerged numerous fastener systems which claim to improve the fatigue life of the joined components. The design engineer requires to know how these fastener systems will perform in his particular application such that he may choose a safe but economic solution. This requirement was recognized by AGARD and two coordinated programmes have been completed which have addressed this problem. The 'Critically Loaded Hole Technology'(1) programme was a pilot programme which established that consistent fatigue data can be generated in complex fatigue tests between a number of participating countries. It examined principally the effects of hole quality on the fatigue performance of open hole and low load transfer joint specimens. A comprehensive follow on programme, the Fatigue Rated Fastener Systems (FRFS) programme(2), has now been completed. This examined the fatigue performance of a range of fastener systems in many different joint configurations in different materials with a selection of hole preparation techniques and installation parameters. A large amount of valuable design data was generated on the different specimen types. Comparison of different test data was achieved using core programmes of specified parameters in which all countries participated.

In order to facilitate such comparisons in future work it is necessary that a number of standard fatigue specimen geometries are defined and used in conjunction with the standard loading sequences that have been developed in recent years. Accordingly an AGARD group entitled 'Standard Mechanical Joint Fatigue Specimens' was established(3) with the task of defining a number of standard joints for fastener evaluation. The aim was not to design new joints, but to assess in some detail a number of the joints used in the FRFS programme. This is the final report of the AGARD working group, the participants of which are given in Table 1.

## 2 PROGRAMME OVERVIEW

The most important requirement of any standard specimen is that it should be representative of the structural feature which it is to simulate. In the case of joints, the main parameters which need to be represented are the amount of load transferred by and bypassing the fastener, the amount of secondary bending and the way in which these are controlled. The FRFS programme concluded that the primary parameter is in fact secondary bending. Accordingly the standard mechanical joint programme is split into two parts. Part 1 considers joints with no or low secondary bending and is described in section 2.1. Part 2 considers joints with high secondary bending and is described in section 2.2.

### 2.1 No or low secondary bending programme

In aircraft wing construction there are many areas which exhibit no or low secondary bending. Examples of this are span-wise joints, either skin-to-spar or skin-to-stiffener. The skin-to-stiffener joint will contain very low load transfer and should not be a fatigue-critical area. The skin-to-spar joint will for the most part be a low load transfer situation but depending on local design may have a high load transfer near the wing root and become fatigue critical.

Chord-wise joints are on the other hand predominantly high load transfer situations. Where double shear butt joints occur (i.e. no secondary bending) fatigue resistance is generally good. It is arguable therefore whether this type of joint is fatigue-critical. Chord-wise joints with single shear fasteners generally exhibit significant amounts of secondary bending and are considered in Part 2 of this exercise (section 2.2).

It is therefore necessary in this part of the programme to consider a number of joints which exhibit various degrees of load transfer and to pose the question:

Do all of the joints considered, rate fatigue resistant fastener systems in the same way?

There was conflicting evidence from the FRFS programme on this question. If this criterion is satisfied for all of the joints considered then only one specimen type needs to be defined as a standard. If this criterion is not satisfied, then a minimum number of joints need to be selected.

Many laboratory joint specimens with no or low secondary bending are intended to be as realistic as possible. Thus many contain several fastener rows and several fasteners per row. On the other hand there are many simple and much cheaper joints which only contain one or two fasteners. The main requirement for a standard specimen is that it should produce a rating of fastener systems. It was considered by the working group that the simple joints were capable of performing this task. The complex joints which more accurately represent the lateral stress gradients and load transfer distributions between fastener rows were considered to be unnecessary. The working group also considered that if complex joints were defined as standard designs, most researchers would not use them because of their cost. This would defeat the main aim of the exercise.

### 2.2 High secondary bending programme

The structural feature of main interest in this part of the exercise is a single shear chord-wise wing joint. The specimen design may be relevant to other single shear connections such as lap joints in a pressure cabin, but the essential features of a chord-wise wing joint must be represented in the specimen design. The main features to be modelled are the amount of load transferred (LT) by the fastener and the amount of secondary bending (SB) of the joint. There is currently very little data available on these values in real structures. However LBF reported in 1974(4) that some 60% of aircraft joints studied had an SB ratio of 0.1 - 0.4, 16% had a ratio from 0.4 - 0.8 and a further 15% in the range 0.8 - 1.4. The range of SB values for wing skin attachments was 0 - 0.4. Specimens with SB values of 0.1 or less are considered in Part 1 of this exercise (section 2.1). Joints with very high SB (>0.8) are not considered in this programme. In view of the results of the FRFS programme, it is felt that there is no requirement for a standard fatigue test specimen for fastener evaluation with such a high SB ratio since life-enhancing fastener systems did not produce significant life improvements. Emphasis in part 2 of this exercise is therefore

placed on joints with an SB ratio in the range 0.2 to 0.5. The load transferred by the fastener has been shown to be of lesser importance than the amount of secondary bending (2). However in a chord-wise wing joint the load transferred by a fastener is likely to be significant. LT values in the range 20% - 50% are therefore considered in the exercise.

The LT and SB values discussed in the above paragraph are not absolute values but depend on loading conditions. Similarly in a laboratory joint these values will depend on the load applied, load sequence and load history already applied. The LT and SB values however will be predominantly dependent upon specimen geometry and fastener flexibility and fit. The experimental joints are broadly sub-divided into two groups, those in which LT and SB are significantly altered by the fastener fit and flexibility (fastener-dominated joints) and those which are not (geometry-dominated joints). In aircraft structure it is not clear which class of joint predominates, but current opinion is that geometry-dominated joints are more common among those where fatigue may be critical.

In view of the load transfer and secondary bending considerations detailed above the high secondary bending phase of the programme is quite complex. There are a number of joints under consideration which must be assessed in a number of ways. Firstly it must be confirmed by measurement that the LT and SB requirements are fulfilled i.e. the average SB ratio is in the range 0.2 to 0.5 and the average LT is in the range 20% - 50% over a range of applied loads and a range of fastener installations. These criteria must apply when the joint is in a 'stabilised' condition i.e. after a period of loading when movement in the joint has stabilised. From these measurements, with a range of fastener installations, we can identify whether particular joints are fastener or geometry dominated. Characteristic values of LT and SB can also be assigned to each joint. These characteristic values must be considered in conjunction with the results of a fatigue testing programme. As discussed in the previous section a fatigue testing programme is required to establish if all of the joints considered, rate fatigue resistant fastener systems in the same way.

From the results of the LT and SB measurements and from the fatigue test programme, a number of joints must then be selected as standard specimens. In order to determine which joint or joints should be defined as standards, a selection procedure was defined by the working group. This selection procedure starts by considering whether all of the joints yield similar results in both ranking and fatigue rating, with the use of fatigue resistant fastener systems. It may be that a number, but not all of the specimens produce similar results. If this is the case then one joint may be selected from this common group. Further considerations should be made of the remaining joints to assess their importance. It is possible that the fastener-dominated joints will yield different results to the geometry-dominated joints, in which case one joint from each group must be selected. It may also be the case that the value of SB may overshadow any other factors in determining the relative life improvements. In this case it would be preferable to select one joint which could produce different values of SB by simple geometric changes.

### 3. STANDARD SPECIMEN DESIGNS

As discussed in the introduction (section 1), the scope of the programme was to look in more detail at the joints used in the FRFS programme. A large number of specimens with no or low secondary bending were used which exhibit various amounts of load transfer. In order to consider which joints should be evaluated in detail for this programme, specimens were sub-divided into three groups: no load transfer, low load transfer and high load transfer. Specimen geometries considered and those chosen for evaluation in the three categories, are described in sections 3.1, 3.2 and 3.3 respectively.

In contrast however few laboratory joints were tested in the FRFS programme which contained secondary bending in the range 0.2 to 0.5 and were relatively simple. The joints considered in detail for this programme are described in section 3.4. The plate materials and hole preparation procedures for both parts of this programme are described in section 3.5.

#### 3.1 No load transfer specimens

Two designs of no load transfer specimen were considered, both of which were tested in the FRFS programme, one design was from France and the other from Sweden. The French design was chosen for inclusion at the AGARD FRFS meeting in San Antonio and is shown in Fig 1. The most striking feature of the specimen is the offset fastener hole resulting in different stress gradients on either side of the hole. This represents the end fastener in a row where the stress gradient is asymmetric. The overall fastener load transfer is zero, though frictional load transfer may occur through the sideplate. The secondary bending is considered to be negligible. The specimen consists of a dogbone with a small non-load carrying element attached via the fastener. The small element and the dogbone undergo the same hole preparations and surface treatments, as described in section 3.5.

#### 3.2 Low load transfer specimens

Two designs of low load transfer specimens were considered, both of which were tested in the FRFS programme. Both designs are reverse double dogbone specimens, one previously used by AGARD in the critically loaded hole technology programme and one developed in the UK. They are similar in concept and geometry, but the UK joint is significantly smaller. The UK joint (Fig 2) was selected for the following reasons.

1. Buckling problems associated with the AGARD joint - stiff buckling guides may be necessary. These are undesirable in that if the buckling is constrained, the LT and SB of the joint will be altered.
2. Cost.
3. Data was going to be available on the UK joint using the same material, fastener systems, surface and hole preparations as the high load transfer joint.

Measurements of LT and SB on the AGARD joint were made in the FRFS programme(2). It was shown that each of the two fasteners transfer about 5% of the load. The secondary bending was measured and found to be in the range 0.1 to 0.25.

### 3.3 High load transfer specimens

Eight different designs of double shear medium or high load transfer joints were tested in the FRFS programme, each joint containing between two and sixteen fasteners. Complex joints with multiple fastener rows and multiple fasteners in each row were rejected for the reasons described in section 2.1, namely that the important requirement for a standard joint is its ability to rate fastener systems and it was considered that a simple two fastener joint was adequate for this purpose. A load transfer of 30 — 50% in the test section is the main requirement. The selection was thus based on simplicity and cost. Test data on the UK joint, shown in Fig 3, was already available from the FRFS programme and it was selected for comparison with the no and low load transfer joints.

### 3.4 Specimen designs with high secondary bending

Four specimen designs were reviewed, though only three were considered for use as standard joints. The reason for including test data on the fourth is for comparison, since there is little data available on joints which meet the LT and SB requirements of this programme. The Swedish 'X' joint shown in Fig 4 is the joint which was considered unsuitable as a standard. The joint contains 16 fasteners and has very high lateral stress gradients both of which are undesirable features in a standard joint. It was used in the AGARD 'Fatigue Rated Fastener System' (FRFS) programme and the results presented here were obtained as part of that programme. Fig 5 shows the commonly used 1 1/2 dogbone specimen which was also tested as part of the FRFS programme by the Netherlands and USA. Fig 6 shows the UK Q-joint which is a modified version of the joint used in the FRFS programme having 1/4" diameter fasteners in the controlling section. Fig 7 shows the detailed design of the Swedish U-joint which was not tested in the FRFS programme. This joint is a derivative of the X-joint used in the FRFS programme and was specifically designed for this investigation. It is essentially a single column X-joint but with a U-channel splice plate instead of the flat plate used in the X-joint construction. Two and four column U-joints have been used successfully in the past, but this is the first assessment of the single column variant.

### 3.5 Specimen requirements

Joints in Part 1 of the exercise were manufactured from a common batch of 7010 — T7651 material. Joints in Part 2 were manufactured from 7050 — T76 material from the same batch as that used in the FRFS programme. The chemical composition and mechanical properties of both materials are given in Table 2. Holes were produced by the general procedure: pilot drill, drill, ream, cold-work, ream, deburr, measure hole diameter, countersink. Variations to this procedure for individual fastener systems are given in sections 4.1 to 4.4. All specimens were wet assembled using PR-1422 for Part 1 specimens and PR-1431-G for Part 2 specimens.

## 4. FASTENER SYSTEMS

In order to assess whether the joints described in the last section rate fastener systems in the same way, they must be tested with a range of fastener systems. Fatigue resistant fastener systems rely on one, or a combination of two or three mechanisms. These are clamping, interference fit and cold-working. The fastener systems chosen to assess the joints must therefore cover a range of combinations of these parameters which are typically used in practice. Accordingly four cases were chosen for each part of the exercise which cover this range. The four cases are described below and are based on the systems used in the FRFS programme. Systems 1A and 2A are identical to FRFS-A and systems 1B and 2B are identical to FRFS-B. Systems 1C and 2C are similar to FRFS-C, which specified an interference fit of  $90 \pm 10 \mu\text{m}$ .

#### Part 1 No or low secondary bending

	COLD-WORKED	FASTENER	FIT
1A	NO	HI-LOK	Clearance $20 \pm 10 \mu\text{m}$
1B	YES	HI-LOK	Interference $25 \pm 10 \mu\text{m}$
1C	NO	HI-TIGUE	Interference $110 \pm 10 \mu\text{m}$
1D	YES	HUCK-EXL	Interference $120 \pm 10 \mu\text{m}$

To check these fits, measurements of hole and fastener diameters were made for each joint and are summarised in Annex 1. The four fastener systems chosen for conditions 1A to 1D were HI-LOK, HI-LOK in BOBING CX cold-worked hole, HI-TIGUE and HUCK EXL respectively.

## Part 2 High secondary bending

	COLD-WORKED	FASTENER	FIT
2A	NO	HI-LOK	Clearance $20 \pm 10 \mu\text{m}$
2B	YES	HI-LOK	Interference $25 \pm 10 \mu\text{m}$
2C	NO	HI-TIGUE	Interference $70 \pm 10 \mu\text{m}$
2D	YES	HI-TIGUE	Interference $70 \pm 10 \mu\text{m}$

To check these fits, measurements of hole and fastener diameters were made for each joint and are summarised in Annex 1. The four fastener systems chosen for conditions 2A to 2D were HI-LOK, HI-LOK in BOEING CX cold-worked hole, HI-TIGUE and HI-TIGUE in BOEING CX cold-worked hole.

Details of each fastener system and hole preparations are described in sections 4.1 to 4.4. Sketches of the fastener systems are shown in Fig 8.

## 4.1 HI-LOK in plain hole (1A and 2A)

The HI-LOK fastener can be installed with light clearance or interference fits. It is available in steel and titanium with a variety of coatings. HI-LOKS used in this investigation were steel, 6.35mm dia. pins installed with a light clearance fit and assembled with shear-off type collars, or K-fast nuts. The pin and collar part numbers are given in Annex 2.

## 4.2 HI-LOK in cold-worked hole (1B and 2B).

The BOEING CX split sleeve process cold-expands the fastener holes prior to assembly. A mandrel is inserted through the fastener hole and a split sleeve passed over the mandrel, into the fastener hole. The mandrel is then pulled through the sleeve using a compressed air powered puller. The sleeve is discarded and the hole reamed to size. Specimens are then deburred and countersinks drilled. The HI-LOK fastener (as described in 4.1) is then installed with a light interference fit and assembled with a shear-off type collar, or K-fast nut.

The cold-working was carried out using F.T.I. standard tooling to the 8-0-N specification for Part 1 (the no or low secondary bending joints), and to the 6-3-N specification for Part 2 (the high secondary bending joints).

## 4.3 HI-TIGUE in plain hole (1C and 2C) and HI-TIGUE in cold-worked hole (2D)

The HI-TIGUE fastener is an interference fit fastener. The pin has conventional parallel sides of larger diameter than the hole, but has a small lubricated bead at the threaded end which expands the hole as it is assembled, allowing the parallel pin to be drawn through the hole, resulting in an interference fit. The pin must be drawn through the hole using a rivet gun and then the nut assembled and torque tightened to 10.2 – 11.3Nm.

The hole diameters required to give the fits described in section 4 are presented in Table 3. For the case of HI-TIGUE in cold-worked hole (2D), cold expansion was carried out using F.T.I. standard tooling to the 8-0-N specification using a common mandrel supplied by FOKKER (Q-joints and 1 1/2 dogbone only). A final reamer was also supplied by FOKKER to give the required fits in the Q-joints and 1 1/2 dogbone specimens. The pin and collar part numbers are given in Annex 2.

## 4.4 HUCK EXL (1D)

This fastener system combines all three fatigue life improvement mechanisms. It is a two part fastener pin, the first part cold working the hole as it is drawn through, the second part being a parallel sided pin which when installed produces an interference fit. A collar is placed over the interference fit pin and swaged into locking grooves, whilst the cold-working part is gripped and pulled until it separates from the installed pin. The complete operation is carried out using a special HUCK pulling tool.

The part numbers of the pins and collars are given in Annex 2. It should be noted that this fastener type was not available in the -6 length, consequently for the no load transfer specimen, the -8 length was used in conjunction with a thicker (7mm) washer.

## 5 TESTING PROGRAMMES

For both parts of the programme fatigue tests were carried out using the FALSTAFF loading sequence. Five fatigue tests per condition were performed at each of two stress levels. The details of the testing for Part 1 and Part 2 of the exercise are given in sections 5.1 and 5.2 respectively.

## 5.1 No or low secondary bending test programme

The fatigue tests were carried out at two sites; the no load transfer specimens were tested at CEAT, France, and the low and high load transfer specimens were tested at British Aerospace Woodford, UK. The specimen blanks were all manufactured by Cleveland Guest, UK and assembled at British Aerospace, Warton. The stress levels chosen were 280MPa and 350MPa on

the net section for the peak FALSTAFF level. The high load transfer specimens were tested at 280MPa and 375MPa, the life at 350MPa being calculated assuming a linear relationship between log stress and log life.

Tests were carried out using servo-hydraulic fatigue machines, these were:-

UK — Mayes 100kN capacity.

France — CEAT 100kN capacity.

Testing on the UK machines was carried out at a mean cyclic frequency of 11Hz which gives a frequency of 1.8Hz for the maximum load excursion. Testing on the French machines was carried out at a mean cyclic frequency of 12Hz, giving a frequency of 2Hz for the maximum load excursion.

## 5.2 High secondary bending test programme

As described earlier, the information required from the test programme is twofold; the load transfer and secondary bending characteristics of the joints and the fatigue endurance. A number of specimens were strain gauged and measurements of LT and SB made using the procedures described in Annex 3.

The fatigue test stress levels varied from joint to joint, depending on the amount of secondary bending. The proposed two stress levels are defined as those levels which produced fatigue endurances of 5000 and 15000 FALSTAFF flights with the datum (clearance fit HI-LOK) fastener installed. These stress levels were not universally used in the programme. The net section and gross section stress levels for the peak applied FALSTAFF load used by each participant are given below:-

	Net section	Gross section
UK-Q joint	280MPa and 350 MPa	210MPa and 263MPa
NL/I-1 1/2 dogbone	268MPa and 335MPa	200MPa and 250 MPa
S-X joints	200MPa and 267MPa	150MPa and 200 MPa
S-U joint	276MPa and 345MPa	200MPa and 250 MPa

## 6 RESULTS AND DISCUSSIONS

The results and discussions of the two parts of the programme are presented in this section. The no or low secondary bending part of the exercise is discussed in section 6.1 and the high secondary bending part in section 6.2.

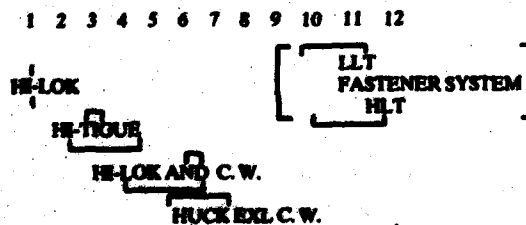
### 6.1 Results and discussions of the no or low secondary bending tests

The fatigue test results from the no load, low load and high load transfer joints are given in Tables 4, 5 and 6 respectively. The relative life improvements over the datum system (HI-LOK fastener in a clearance fit hole) are given in Table 7. The life improvement factors are based on the log mean endurances for each test condition. In view of a number of problems involved with the testing of the no load transfer joint, these results are discussed separately. Section 6.1.1 discusses the results of the low and high load transfer joints, and section 6.1.2 the no load transfer joint.

#### 6.1.1 Low and high load transfer joints

As discussed earlier in section 2.1, the joints have to be assessed in terms of life improvement factors. As can be seen from Table 7, all of the fastener systems are rated in a similar way by the two joints. The life improvement factors are consistently higher at the higher stress level, markedly so for the HUCK and HI-TIGUE fasteners. This is perhaps to be expected with interference fit fasteners, the magnitude of any beneficial compressive residual stress being controlled by the peak of the applied loading. This is not expected however for the case of cold-working, where more benefit is expected at lower stresses. The ranking of the fastener systems is consistent for the two joints considered and is summarised below:-

Life improvement ratios, based on log mean lives.



The absolute fatigue lives of each joint are also very similar under the same test conditions. Log mean lives of each specimen type are within 35% of each other under identical test conditions. It was noted however subsequent to testing that the low load transfer joints had been assembled and tested with titanium fasteners instead of steel. The test data are plotted in Figs 9 and 10 for the low and high stress levels respectively. In view of the high scatter in the data, comparing the life improvement ratios on a log mean basis is not considered sufficient, as it may give a false impression of expected life improvements. The effect of scatter on life improvement ratios is therefore discussed in Annex 4. The effect of fastener type on fatigue crack origins must also be considered and detailed failure sites are given in Annex 5. General observations are also made on the effect of fastener type in the same annex.

### 6.1.2 No load transfer joints

The no load transfer joints showed scratches and surface dents received in transit from the UK to the testing laboratories in France. These damaged areas proved to be the initiation sites in over one third of the specimens. Of the remaining specimens, one half of the failures initiated in the test section and one half initiated in the dogbone radius. The fatigue test results are given in Table 4, from which a number of observations can be made. Failures from the dogbone radius are independent of the fastener system installed and hence the fatigue lives are also independent. Failures at the high stress level initiating from surface scratches produce fatigue lives lower than those failing from the dogbone radius. This is not the case at the lower stress level. In view of the fact that one third of the specimens failed from no apparent defect in the dogbone radius it must be concluded that this specimen is not suitable for fastener evaluation. The stress concentrating effect of the hole is readily overcome by fatigue resistant fastener systems. Fatigue failures therefore occur at an alternative site of stress concentration. A general conclusion can therefore be drawn, that a stress concentration greater than that of an open hole is required in a standard joint for fastener evaluation. The greater concentration can be simply achieved by using a joint in which some load is transferred by the fastener system. Other designs of no load transfer joint have been successfully used for fastener evaluation(2) but have not been tested with such extremes of interference fit and cold-working.

### 6.2 Results and discussion of the high secondary bending tests

A change in design of the UK Q-joint has meant that the test results have been obtained on two different designs of joint. An assessment of the importance of this change is made in Annex 6. The results of the LT and SB measurements on each joint are discussed in section 6.2.1. The fatigue test results are discussed in section 6.2.2.

#### 6.2.1 Load transfer and secondary bending results

The results of the load transfer and secondary bending measurements on each of the joints are presented and assessed in this section. The results of the Q-joint, 1 1/2 dogbone, U-joint and X-joint are presented in subsections a, b, c and d respectively. Both the LT and SB measurements vary to some degree with applied load. The values of SB at the peak applied load is important in determining if residual stresses are formed (or existing residual stress fields are modified) and if so their resulting magnitude around the fastener holes. This has a significant effect upon the damage done by the ensuing load cycles. Most fatigue damage however is done by the relatively lower load cycles, typically the maximum damage occurring at a stress range of about 1/3 of the level 32 peak stress. The SB values at the damaging 1/3rd peak stress level are also calculated as a % of the SB values at the peak load, i.e. if the SB value for a joint is 0.5 and the 1/3rd ratio is 80% then the peak SB is 0.5 and the SB at 1/3rd FALSTAFF peak load is 0.4.

##### a) Q-joint measurements

Measurements have been made on both variants of the Q-joint (3/16" and 1/4" fasteners in the controlling section) with HI-LOK fasteners installed in plain and cold worked holes. The results are presented in Tables 8 and 9 for the 1/4" and 3/16" fasteners respectively. Measurements of LT and SB with HI-TIGUE fasteners installed in plain and cold worked holes are presented in Table 10. A comparison of the results with different diameters of HI-LOK fasteners is made in Annex 6.

For each set of test data it is apparent that cold working does not significantly affect the SB ratio but does affect the LT. The effect of fastener fit however is quite marked. Comparing Tables 9 and 10, it can be seen that high interference fit fasteners (2C and 2D) produce lower LT and SB values in the test section than the light clearance/light interference fit fasteners (2A and 2B). This variation in values however is quite small compared with other fastener-dominated joints (e.g. 1 1/2 dogbone). The Q-joint is therefore classed as a fastener-dominated joint, but with a low fastener dominance. A summary of these measurements is presented in Fig 11.

The effect of applied load level on the LT and SB values is similar with any of the fastener systems installed, the 1/3rd load ratio being between 63 - 73% for the four fastener systems.

##### b) 1 1/2 dogbone measurements

Measurements have been made on the 1 1/2 dogbone specimen with HI-LOK and HI-TIGUE fasteners installed in plain and cold worked holes. The results are presented in Tables 11 and 12 respectively. Values of load transfer vary little with either applied load or fastener fit. Load transfer values at peak applied load vary only from 24% to 31% for the four fastener systems, LT increasing with fastener interference. The secondary bending ratio however varies both with applied load and fastener fit. The variation of secondary bending with applied load shows a reversal of the bending direction with both the HI-LOK fastener installations (2A and 2B). In the HI-LOK in a plain hole case, the rate of change of SB ratio with applied load is quite extreme. With HI-TIGUE fasteners installed, however, very little variation of secondary bending with applied load is found, the 1/3rd load ratio being about 80% for both plain and cold worked holes. Comparing the SB ratios for the four fastener installations shows a large dependence on the fastener system. The 1 1/2 dogbone specimen is therefore classed as a fastener dominated joint. A summary of the measurements at peak FALSTAFF load is presented in Fig 12.

##### c) U-joint measurements

The results of secondary bending measurements on the U-joint with HI-LOK and HI-TIGUE fasteners in plain holes are given in Table 13. Load transfer measurements were made on this specimen but evaluation of the results was not realistic with so few strain gauges; the LT was assumed to be 50 - 55%. The SB measurements were made with and without mid-side supports. A considerable difference in SB values was observed when comparing the results with and without support. A peak value of 0.3 without support and 0.4 with support was measured with HI-LOK fasteners installed and 0.26 and 0.34 respectively with HI-TIGUE fasteners installed. SB values vary little with applied load, the 1/3rd load ratio varying

between 82% and 100% for the four cases. The variation of SB values with fastener fit is similar to that found in the Q-joint. The reduction in SB values in the U-joint with increasing fit is 13% to 16% compared with a reduction of 20% to 27% in the Q-joint.

d) X-joint measurements

Measurements of SB have been made on this joint, with the datum fastener system installed. The results of the SB measurements give values between 0.4 and 0.8 (depending on location) at the peak applied load. The average value across the test section is 0.61. Load transfer measurements were not evaluated as too few strain gauges were used to give realistic results.

6.2.2 Fatigue test results

The fatigue test results are presented in Tables 14 to 17 for the Q-joint, 1 1/2 dogbone, X-joint and U-joint respectively and discussed in sections a) to d) respectively.

a) Q-joint endurances

Fatigue testing of the Q-joint, as discussed earlier, has been performed with two variants, one with 3/16" diameter and one with 1/4" diameter fasteners in the controlling section. The HI-LOK fasteners in plain and cold worked holes (2A and 2B) were tested with the smaller fasteners in the controlling section. The HI-TIGUE fasteners in plain and cold worked holes (2C and 2D) were tested with the larger fasteners in the controlling section.

Comparing first the results for HI-LOK fasteners in plain and cold-worked holes (see Table 14), the expected benefit produced by cold-working alone is offset by the relatively high secondary bending in the joint. The resultant stresses at the interface of the joint were some 40% higher than the axial stresses applied. The high stress levels in the FALSTAFF sequence thus quickly wipe out the beneficial compressive residual stresses induced by the cold working process.

In contrast, however, the interference fit HI-TIGUE fasteners provide considerable improvement in fatigue performance. The reason for this benefit is threefold. Firstly the fretting damage is considerably reduced due to the lower relative slip caused by the interference fit. Secondly a compressive beneficial residual stress is formed by the application of the highest load in the FALSTAFF sequence. The secondary bending causes the surface stress at the joint interface to be 40% higher than the axially applied stress. Thus a large compressive residual stress is formed at the interface on unloading. Thirdly the stress concentration factor is considerably reduced by the high interference, thus reducing the damaging effect of subsequent alternating loading. The combination of these three effects causes a considerable increase in the fatigue endurance. The combination of an interference fit fastener and a cold worked hole appears to give an even greater enhancement in fatigue endurance. This enhancement however does change the failure mode of the joint. Three of the specimens tested with HI-TIGUE fasteners in cold worked holes, failed away from the test section, one at the edge of the gripped area, one at the controlling section, and one at the end of the lap plate. All of the remaining specimens with cold work and interference fit had at least one crack initiating due to fretting in the test section, but not from the fastener holes. It must be concluded that the limit of life enhancement of this joint is being approached as failure is beginning to occur remote from the fasteners. However the joint is considered to be capable of rating most fastener systems under conditions of high secondary bending.

b) 1 1/2 dogbone endurances

Testing of the 1 1/2 dogbone specimen has been undertaken at two sites. Testing with HI-LOK fasteners installed in plain and cold worked holes (2A and 2B) was undertaken at NLR as part of the FRFS programme. Testing with HI-TIGUE fasteners installed in plain and cold worked holes (2C and 2D) was undertaken at the University of Pisa. In view of the possibility of high secondary bending stresses occurring in this specimen, it was required that the testing was performed using fatigue test machines of a similar stiffness at both sites. To ensure that a change in test machine did not affect fatigue lives, a number of check tests were undertaken at the University of Pisa. These results are presented in Table 15, along with the other fatigue test results of the 1 1/2 dogbone specimen.

The compatibility tests show that with clearance fit HI-LOK fasteners installed and tested at the higher stress level, consistent data was produced at both sites. The 1 1/2 dogbone specimen is a fastener-dominated joint, so that the amount of secondary bending is dependent on the fastener fit. The secondary bending in the cold-worked light interference fit joint (2B) is some four times greater than that in the clearance fit joint (2A). The beneficial compressive residual stress field formed by the cold working process is offset by the detrimental increase in local surface stress. As a consequence there is no increase in fatigue endurance over the datum system using cold-working and light interference fit. The data on joints with HI-TIGUE fasteners in plain holes (2C) shows that no improvement in fatigue endurance is achieved with the use of interference fit fasteners. The results of the fatigue tests with HI-TIGUE fasteners installed in cold-worked holes (2D) also show no life improvement over the datum HI-LOK system. Both of these observations are attributed to the increase in secondary bending of the joint with increased fastener fit. The SB ratio with high interference fit fasteners has increased to a peak value of 0.45 compared with 0.22 for light interference cold-worked holes and less than 0.1 for clearance fit holes. In fact, the increased SB ratio for the HI-TIGUE fastener in a plain hole (2C), causes a reduction in fatigue life compared with the datum HI-LOK system. Cold working of the hole before installation of a HI-TIGUE fastener (2D), however, causes an increase in fatigue life over the HI-TIGUE in a plain hole (2C). This increase only brings the fatigue life of the HI-TIGUE fastener in a cold worked hole back to that of the datum system. It is considered that from these results, the 1 1/2 dogbone specimen is not suitable for the evaluation of fatigue resistant fastener systems.

c) X-joint enhancement

Fatigue testing of the X-joint was undertaken as part of the FIFE programme. The results obtained are presented in Table 16. The beneficial effect of cold working is clearly demonstrated in this joint, with life improvement factors of about two being obtained at both stress levels. It was noted however that cold worked specimens tested at the low stress level all failed in the splice plate; life improvement factors are therefore not relevant. Measurements of load transfer and secondary bending have not yet been made with both fastener systems installed. It is not possible therefore to assess the importance of these results. From the measurements on the datum system however it is surprising to find that cold working doubles the fatigue endurance despite the high value of secondary bending (0.6 with the datum system).

d) U-joint enhancement

The fatigue test results of the U-joint specimen are presented in Table 17. Results were obtained at two stress levels with both the HS-LOK and HS-TORQUE fasteners installed in plain holes. Three failures with HS-LOK fasteners installed, occurred in the splice plate. All of the failures with HS-TORQUE fasteners installed, occurred in the splice plate. One non splice plate failure occurred with HS-TORQUE fasteners installed, but this was when the splice plate was of a different material (7010-T73651). All other splice plates were made from 7075-T6 material. It was decided to abort further testing of the U-joint specimen, on the assumption that most failures would occur in the splice plate. It was therefore concluded that the U-joint specimen was not suitable design for fastener evaluation. It should be noted however that specimens with two or four U-channels fastened to the base plate have been used successfully in the past. A future development of the single column U-joint will probably involve thickening the U-channel web from 5 to 6 mm.

7 CONCLUSIONS AND RECOMMENDATIONS OF PART 1, NO OR LOW SECONDARY BENDING

- 1) The low and high load transfer joints tested in this programme under FALSTAFF loading both produced similar fatigue lives under the same test conditions.
- 2) The ranking of all four fastener systems was the same in the low and high load transfer joints.
- 3) The low and high load transfer joints are considered equivalent in rating fatigue resistant fastener systems.
- 4) The no load transfer joint is not recommended as a standard joint for fastener evaluation.

8 CONCLUSIONS AND RECOMMENDATIONS OF PART 2, HIGH SECONDARY BENDING

This investigation has shown the difficulty in designing a joint for fastener evaluation which exhibits typical amounts of load transfer and secondary bending found in practice. All of the joints tested produced a number of failures originating away from the test section under certain conditions. Failure sites are detailed in Annex 5 and are summarised below.

	Failures away from test section using fastener system			
	2A	2B	2C	2D
Q-joint				✓
1 1/2 - daphone			✓	✓
X-joint		✓	-	-
U-joint	✓	-	✓	-

Clearly the U-joint would be rejected as not being able to rate the simpler fastener systems in the designated test section where the load transfer and secondary bending are being controlled. This was also the case for the X-joint. The 1 1/2 daphone specimens exhibit a percentage of failures away from the test section with most fastener systems. The Q-joint behaves similarly when high interference fit fasteners are installed. It is considered that these joints are therefore approaching their limits for assessing fatigue rated fastener system.

The 1 1/2 daphone specimen has been shown to be a fastener-dominated joint in which the secondary bending in the test section is highly influenced by the fastener fit. The expected increase in fatigue life with an increasing degree of interference fit is offset by an increase in secondary bending ratio. In fact a slight reduction in fatigue life was obtained with high interference fit fasteners when compared to clearance fit fasteners. In a real structure it is anticipated that the secondary bending ratio at any location will to some degree be dependent on the fastener fit, but will be predominantly dependent on the local geometry. The 1 1/2 daphone specimen is rejected as not being able to rate fastener systems in a useful way.

The Q-joint is the only specimen which consistently produces failures in the test section. The values of load transfer and secondary bending are predominantly governed by the geometry of the joint and to a lesser degree by the fastener fit. Of the joints considered in this exercise, the Q-joint is recommended as the most suitable for fastener evaluation purposes.

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3. R.COOK and H.H. van der LINDEN. Standard Fatigue Test Specimens for Fastener Evaluation. Paper presented at AGARD meeting, SAN ANTONIO, (April 1983)
4. D.SCHUETZ and H.LOWAK. The effect of secondary bending on the fatigue strength of joints. RAE Library Translation No 1858, (1974)

TABLE 1  
PARTICIPANTS IN THE STANDARD SPECIMENS PROGRAMME

Country	Participants	
France	Centre D'essais Aeronautique de Toulouse - CEAT	I P A Liberge
Italy	University of Pisa	G Cavallini
The Netherlands	National Aerospace Laboratory -NLR	H H van der Linden
Sweden	Saab-Scania	L Jarfall
Sweden	Flygtekniska Försöksanstalten - FFA	B Palmberg
United Kingdom	Royal Aircraft Establishment	R Cook

TABLE 2

A. TYPICAL CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES  
OF 7010-T7651

## CHEMICAL COMPOSITION - UNCLAD

	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Zr	Cr
% Min	1.5	2.2	-	-	-	-	5.7	-	-	-	0.11	-
% Max	2.0	2.7	0.1	0.15	0.3	0.05	6.7	0.05	0.05	0.05	0.17	0.05

Remainder Al

## MECHANICAL PROPERTIES - MINIMUM REQUIREMENTS - L DIRECTION

Tensile strength 530 MPa

0.2% Proof Stress 450 MPa

Elongation % 8  
gauge length 50 mm

## B. TYPICAL CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF 7050-T76

## CHEMICAL COMPOSITION - UNCLAD

	Cu	Mg	Si	Fe	Mn	Zn	Ti	Zr	Cr
% Min	2.00	1.9	-	-	-	5.70	-	0.08	-
% Max	2.60	2.6	0.12	0.15	0.10	6.70	0.06	0.15	0.04

Remainder Al

## MECHANICAL PROPERTIES - L DIRECTION

	Min	Max
Tensile strength (MPa)	573	582
0.2% Proof stress (MPa)	521	552
Elongation % Gauge length 50 mm	12	12.5

TABLE 3

	Hole Dia (Reamed)	CRK Dia	Hole Dia (After Cr)	Remarks
1A Hi-Lok in Plain Hole	6.35 6.37	9.98 10.06	-	Torque tighten to 6.8 - 9.1 Nm
2A Hi-Lok in Plain Hole	6.35 6.37	9.98 10.06	-	Record Value at which collar shears off
1B Hi-Lok in Cr Hole	5.97 6.04	9.98 10.06	6.30 6.32	Torque tighten to 6.8 - 9.1 Nm
2B Hi-Lok in Cr Hole	5.71 5.79	9.98 10.06	6.30 6.32	Record value at which collar shears off
1C & 2C Hi-Tigue in Plain Hole	6.21 6.25	9.93 9.93	-	Torque tighten to 10.2 - 11.3 Nm
1D Huck EKL	6.045 6.17	Produced by Huck Installation Tools		Automatic clamping by Swaging Collar
2D Hi-Tigue in Cr Hole	5.97 6.04	9.93 9.93	Using Reamer supplied	Torque tighten to 10.2 - 11.3 Nm

**TABLE 4**  
**FATIGUE LIVES OF NO LOAD TRANSFER SPECIMENS**

FASTENER SYSTEM	INITIATION SITES AND FATSTAFF FLIGHTS TO FAILURE AND LOG MEAN VALUES AT PEAK APPLIED NET SECTION STRESS (MPa)					
	TEST SECTION		SURFACE DEFECT		DOGBONE RADIUS	
	280	360	280	360	280	360
1A HI-LOK IN PLAIN HOLE		22232 26173  [24122]	88525 112973 115773  [105400]	23140   [23140]	63240   [63240]	28081 23032  [25431]
1B HI-LOK IN COLD WORKED HOLE	77632 129281  [100182]	37873   [37873]	88232 94325 88831  [78802]	16481 14128 17344  [15824]		38730 22380  [29428]
1C HI-TIQUE IN PLAIN HOLE	32173   [32173]	19432   [19432]	96360   [96360]	18830   [18830]	87130 74232 88032 57530 [70137]	24222 29530 31200  [28154]
1D HUCK EXL IN COLD WORKED HOLE	62773 46330 88200  [63538]	20240 22032 21730  [21319]	28373 61373  [41729]	19190   [19190]	65646   [65646]	28631   [28631]

**TABLE 5**  
**FATIGUE LIVES OF LOW LOAD TRANSFER SPECIMEN**

FASTENER SYSTEM	FALSTAFF FLIGHTS TO FAILURE AND LOG MEAN VALUES AT PEAK APPLIED NET SECTION STRESS	
	280 MPa	350 MPa
1A NI-LOK IN PLAIN HOLE	15372	6031
	14329	7772
	20172	5424
	22680	9239
	16572	8572
	17580	7257
1B NI-LOK IN COLD WORKED HOLE	48231	18759
	118194	61325
	203993	46586
	115231	46796
	99031	83591
	108257	46163
1C NI-TIGUE IN PLAIN HOLE	56351	17080
	54772	17729
	53172	22959
	42172	21572
	74772	23372
	55109	20368
1D HUCK EXL IN COLD WORKED HOLE	115021	66231
	97031	33431
	79972	47943
		69611
	96281	52137

TABLE 6  
FATIGUE LIVES OF HIGH LOAD TRANSFER SPECIMEN

FASTENER SYSTEM	FALSTAFF FLIGHTS TO FAILURE AND [LOG MEAN] VALUES AT PEAK APPLIED NET SECTION STRESS		
	280 MPa	375 MPa	350 MPa *
1A HI-LOK IN PLAIN HOLE	37898 23172 30839 34922 14821 26875	7572 4031 3559 3431 2959 4060	6346
1B HI-LOK IN COLD WORKED HOLE	51172 76759 224420 166196 93021 106366	31759 34525 27772 27359 30212	40680
1C HI-TIGUE IN PLAIN HOLE	66624 32796 52172 123227 41024 56510	34224 27749 27031 12972 20924 23368	28786
1D HUCK EXL IN COLD WORKED HOLE	211711 155031 155172 96986 146572 146560	87511 58880 55172 59929 52972 61814	76057

\* Estimated figure assuming that a log-log S-N curve is linear in this region.

TABLE 7  
FATIGUE LIFE IMPROVEMENT FACTORS

FASTENER SYSTEM	NLT		LLT		HLT	
	280 MPa	350 MPa	280 MPa	350 MPa	280 MPa	350 MPa
1A HI-LOK IN PLAIN HOLE	1	1	<u>17560</u> 1	<u>7257</u> 1	<u>26875</u> 1	<u>6346</u> 1
1B HI-LOK IN CW HOLE			<u>106257</u> 6.05	<u>46163</u> 6.36	<u>106386</u> 3.96	<u>40680</u> 6.41
1C HI-TIGUE IN PLAIN HOLE			<u>55108</u> 3.14	<u>20368</u> 2.81	<u>56510</u> 2.10	<u>28786</u> 4.54
1D HUCK EXL IN COLD WORKED HOLE			<u>96281</u> 5.48	<u>52137</u> 7.18	<u>148580</u> 5.53	<u>76057</u> 11.99

TABLE 8

## LT AND SB MEASUREMENTS - Q-JOINT (1/2" DIA) HI-LOK

SPECIMEN TYPE: Q-JOINT WITH 1/2" DIA HI-LOK FASTENERS

System 2A Plain hole - clearance fit

System 2B Cold worked hole - light interference fit

MAX LOAD (kN): 67

MIN LOAD (kN): -20.5

% of the max load in FALSTAFF	2A		2B	
	LT %	SB ratio	LT %	SB ratio
0	0	-	0	0
16.7	22.3	-	39.4	.131
33.3	28.3	-	44.7	.321
50	32.3	-	46.7	.457
66.7	35.2	-	48.6	.495
83.3	36.2	-	49.7	.498
100	37.6	-	50.3	.494
83.3	38.9	-	51.2	.473
66.7	40.0	-	51.7	.450
50	40.5	-	52.1	.417
33.3	39.6	-	52.6	.341
16.7	39.3	-	54.3	.218
0	0	-	0	0
Minimum load	21.9	-	44.4	.236
0	0	-	0	0

TABLE 9

LT AND SB MEASUREMENTS - Q-JOINT (3/16" DIA) HI-LOK

SPECIMEN TYPE: Q-JOINT WITH 3/16" DIA HI-LOK FASTENERS

System 2A Plain hole - clearance fit

System 2B Cold worked hole - light interference fit

MAX LOAD (kN): 67

MIN LOAD (kN): -20.5

% of the max load in FALSTAFF	2A		2B	
	LT %	SB ratio	LT %	SB ratio
0	0		0	0
16.7	30.4	.192	28.0	.264
33.3	36.1	.341	37.5	.297
50	41.3	.350	42.3	.353
66.7	44.3	.376	44.9	.393
83.3	46.4	.405	47.3	.422
100	49.6	.443	48.7	.441
83.3	51.3	.406	49.8	.402
66.7	52.5	.348	50.3	.352
50	54.5	.318	51.3	.302
33.3	56.8	.309	53.3	.270
16.7	65.3	.336	59.3	.419
0	0	0	0	0
Minimum load	48.3	.418	52.0	.290
0	0	0	0	0



TABLE 11

## LT AND SB MEASUREMENTS 1½ DOGBONE, HI-LOK

SPECIMEN TYPE: 1½ DOGBONE WITH ½" DIA HI-LOK FASTENERS

System 2A Plain hole - clearance fit

System 2B Cold worked hole - light interference fit

MAX LOAD (kN): 60.5

MIN LOAD (kN): -16.2

% of the max load in FALSTAFF	2A		2B	
	LT %	SB ratio	LT %	SB ratio
0	0	0	0	0
16.7	25.9	0.041	22.0	-0.086
33.3	24.7	0.018	22.1	0.031
50	23.8	0.027	22.1	0.142
66.7	24.6	-0.005	22.2	0.187
83.3	25.1	-0.055	23.0	0.210
100	25.7	-0.095	23.8	0.223
83.3	25.5	-0.058	23.3	0.211
66.7	24.3	-0.028	22.9	0.180
50	23.1	0.001	23.1	0.140
33.3	22.4	0.026	23.6	0.060
16.7	20.9	0.026	24.9	-0.023
0	0	0	0	0
Minimum load	12.7	0.054	19.5	-0.055
0	0	0	0	0

TABLE 12

LT AND SB MEASUREMENTS - 1½ DOGBONE, HI-TIGUE

SPECIMEN TYPE: 1½ DOGBONE WITH ½" DIA HI-TIGUE FASTENERS

System 2C Plain hole - high interference fit

System 2D Cold worked hole - high interference fit

MAX LOAD (kN): 60.5

MIN LOAD (kN): -16.2

% of the max load in FALSTAFF	2C		2D	
	LT%	SB .atio	LT%	SB ratio
0	0	0	0	0
16.7	28.8	0.265	30.5	0.425
33.3	28.3	0.424	31.0	0.455
50	27.8	0.504	31.8	0.483
66.7	27.7	0.502	31.5	0.517
83.3	27.7	0.477	31.4	0.506
100	27.8	0.455	31.4	0.481
83.3	27.5	0.412	31.1	0.455
66.7	27.7	0.387	30.9	0.429
50	27.8	0.352	30.8	0.394
33.3	27.3	0.266	30.4	0.310
16.7	26.3	0.060	29.2	0.136
0	0	0	0	0
Minimum load	24.0	0.111	27.2	0.311
0	0	0	0	0

TABLE 13

SB MEASUREMENTS U-JOINT, HI-LOK AND HI-TIGUE

SPECIMEN TYPE: U-JOINT WITH  $\frac{1}{2}$  INCH DIA FASTENERS

SYSTEM 2A HI-LOK IN PLAIN HOLE

SYSTEM 2C HI-TIGUE IN PLAIN HOLE

(a) NO SIDE SUPPORT AND (b) MID SIDE SUPPORT

% of the max load in FALSTAFF	System 2A		System 2c	
	Type (a) SB ratio	Type (b) SB ratio	Type (a) SB ratio	Type (b) SB ratio
0	0	0	0	0
16.7	0.360	0.485	0.260	0.305
33.3	0.305	0.455	0.250	0.300
50	0.305	0.445	0.270	0.320
66.7	0.295	0.420	0.270	0.325
83.3	0.290	0.400	0.255	0.305
100	0.300	0.395	0.260	0.335
83.3	0.295	0.380	0.250	0.310
66.7	0.255	0.355	0.235	0.300
50	0.250	0.335	0.265	0.285
33.3	0.245	0.310	0.260	0.275
16.7	0.335	0.375	0.340	0.325
0	0	0	0	0
Minimum load	0	0	0.140	0.135
0	0	0	0	0

After 10,000 cycles

TABLE 14  
FATIGUE LIVES OF Q-JOINTS

Fastener System	FALSTAFF Flights to Failure and Log Mean Values at Peak Applied Net Section Stress	
	280 MPa	350 MPa
2A HI-LOK IN PLAIN HOLE	12128 14431 12160 13831 14031 <u>13280</u>	3925 2929 3444 4336 <u>3639</u>
2B HI-LOK IN COLD WORKED HOLE	9631 12424 12329 16224 17631 <u>13337</u>	3801 3172 3624 5323 <u>3905</u>
2C HI-TIGUE IN PLAIN HOLE	18530 78032 25225 30860 <u>32572</u>	21730 15825 13573 16385 11173* 8232 <u>14448</u>
2D HI-TIGUE IN COLD WORKED HOLE	25573 77330 45632* 91225 111393* <u>56504</u>	38981 32695 16840* 11159 7997 <u>18364</u>

\* FAILURE AWAY FROM TEST SECTION -  
RESULT NOT INCLUDED IN LOG MEAN VALUE

TABLE 15

## FATIGUE LIVES OF 1½ DOGBONE SPECIMENS

FASTENER SYSTEM	FALSTAFF Flights to Failure and Log Mean Values at Peak Applied Net Section Stress	
	268 MPa	335 MPa
2A HI-LOK IN PLAIN HOLE	18411 60372* 56972 63831 <u>44893</u>	9559 15419 23373 22231 <u>16635</u>
2B HI-LOK IN COLD WORKED HOLE	29572 40431* 58231 35759* <u>39722</u>	13524* 14231 17962* 19172 <u>16045</u>
2C HI-TIGUE IN PLAIN HOLE	30764 36572 <u>33542</u>	9983 16734* 14067* 11780 <u>12899</u>
2D HI-TIGUE IN COLD WORKED HOLE	37146 42640* 38265* <u>39280</u>	19007* 17308* 14946 14564* <u>16358</u>
2D HI-LOK IN PLAIN HOLE COMPATIBILITY TESTS AT PISA		11165 13826 19955 <u>14550</u>

\*FAILURES INITIATING AWAY FROM TEST SECTION

TABLE 16  
FATIGUE LIVES OF X-JOINTS

FASTENER SYSTEM	FALSTAFF Flights to Failure and Log Mean Values at Peak Applied Net Section Stress	
	200 MPa	267 MPa
2A HI-LOK IN PLAIN HOLE	13860* 16972 13180 13772 <u>14375</u>	5329 5590 6280 5425 <u>5646</u>
2B HI-LOK IN COLD WORKED HOLE	42772* 30224* 35631* 27630* <u>33588</u>	10929 11972 11372 6172 <u>9789</u>

\* SPLICE PLATE FAILURE

TABLE 17  
FATIGUE LIVES OF U-JOINTS

FASTENER SYSTEM	FALSTAFF Flights to Failure and Log Mean Values at Peak Applied Net Section Stress	
	276 MPa	345 MPa
2A HI-LOK IN PLAIN HOLE	7831 19311* 10631* 23631 <u>13961</u>	5558* 5729 5431 <u>5571</u>
2B HI-LOK IN COLD WORKED HOLE		
2C HI-TIGUE IN PLAIN HOLE	24372* 17834* 16031* 19572* <u>19217</u>	15424** 13520* 13969* <u>14262</u>
2D HI-TIGUE IN COLD WORKED HOLE		

\* SPLICE PLATE FAILURE (7075-T6)

\*\* SPLICE PLATE MADE FROM 7010 - T73651 (base plate failure)

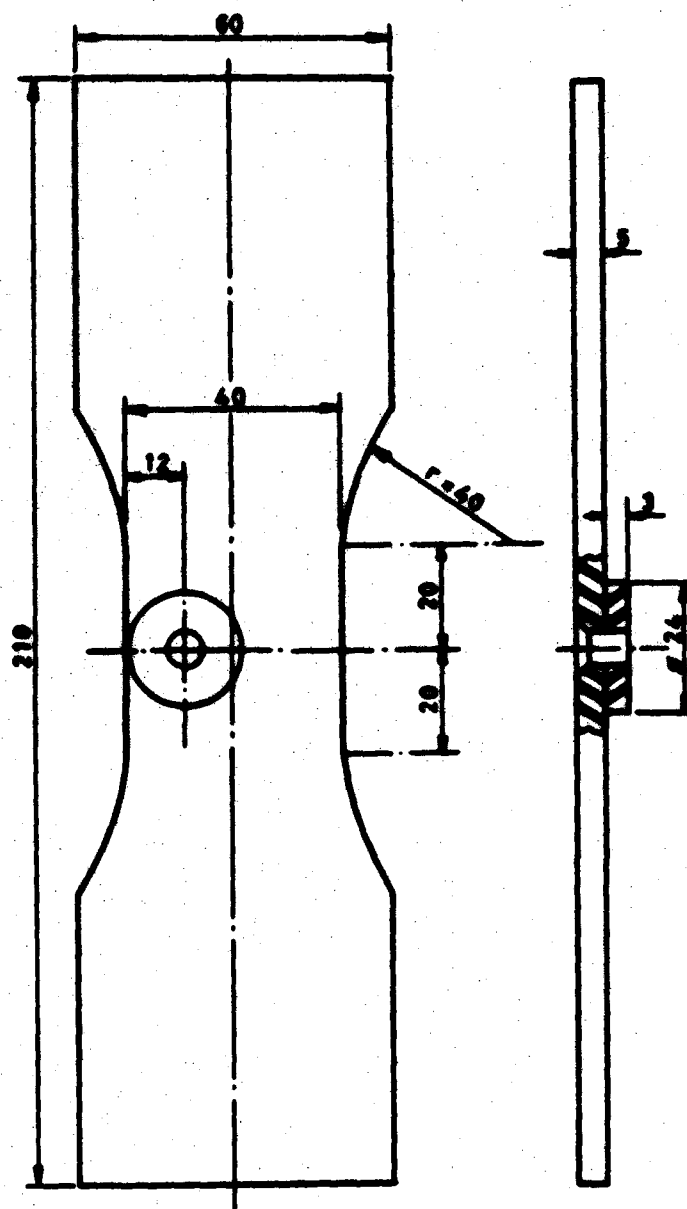


Fig 1 France — no load transfer joint

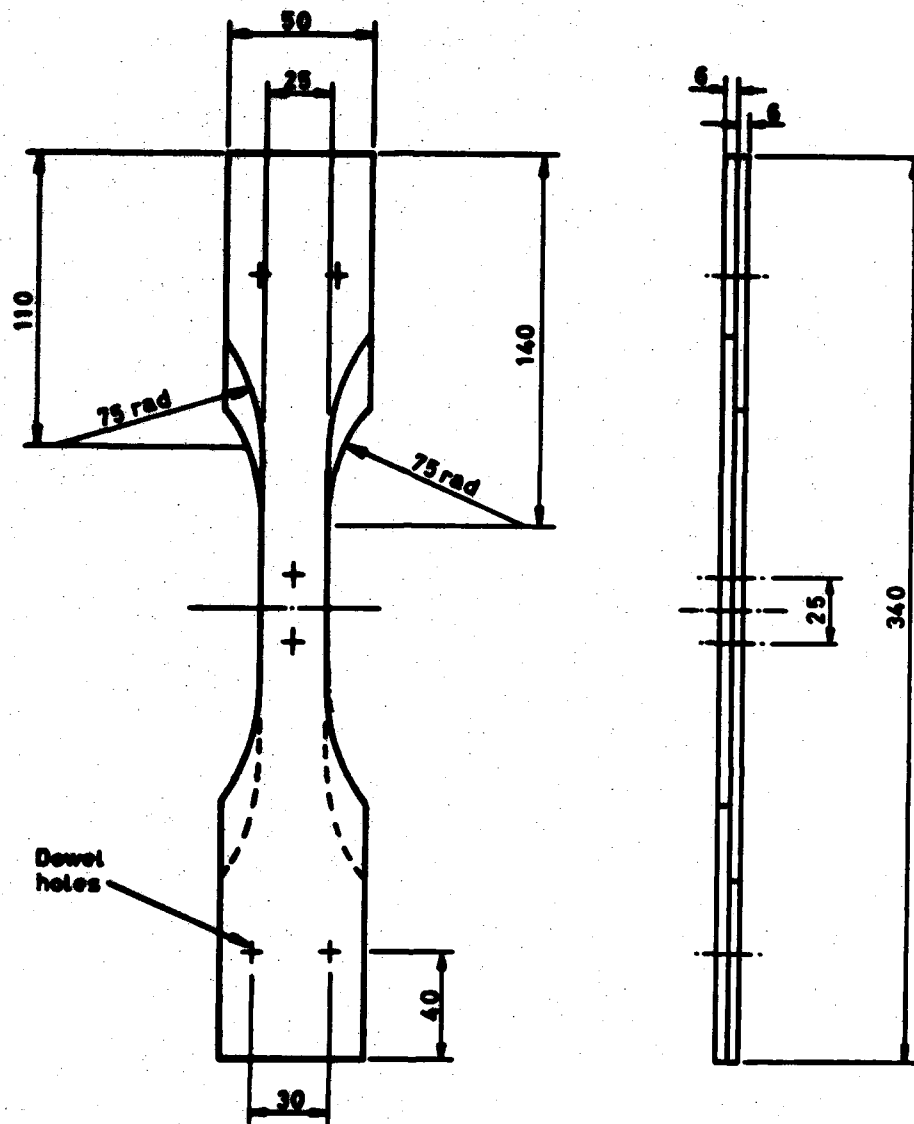


Fig 2 Low load transfer joint

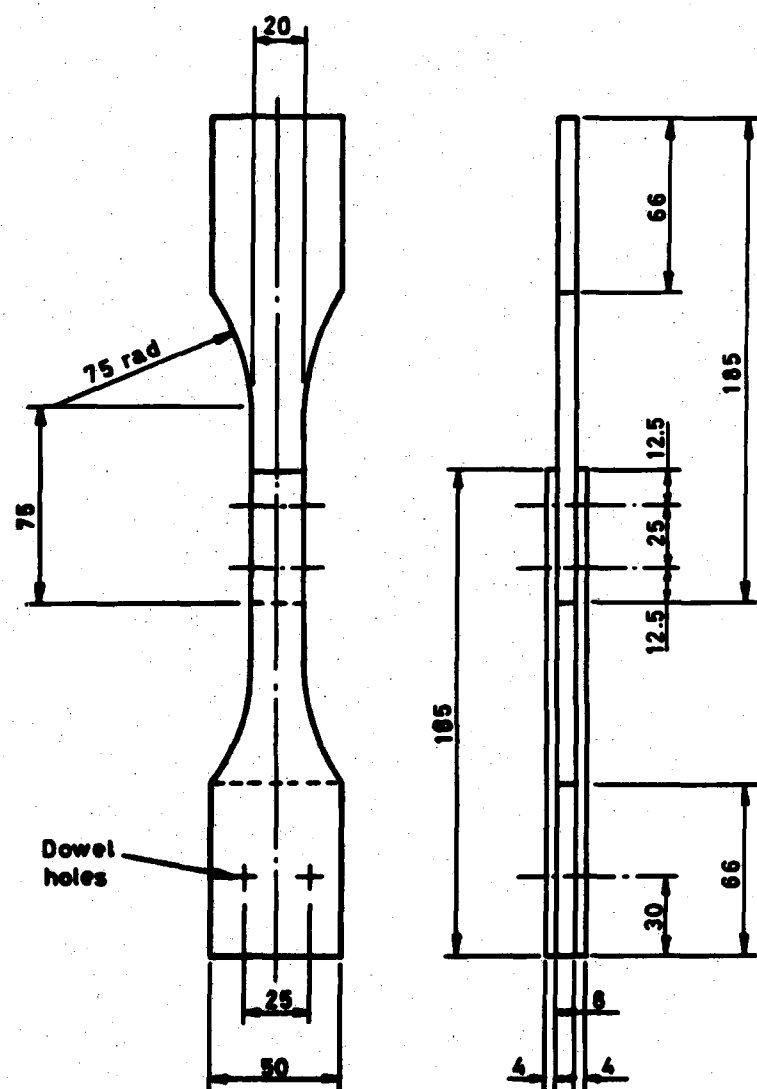


Fig 3 High load transfer joint

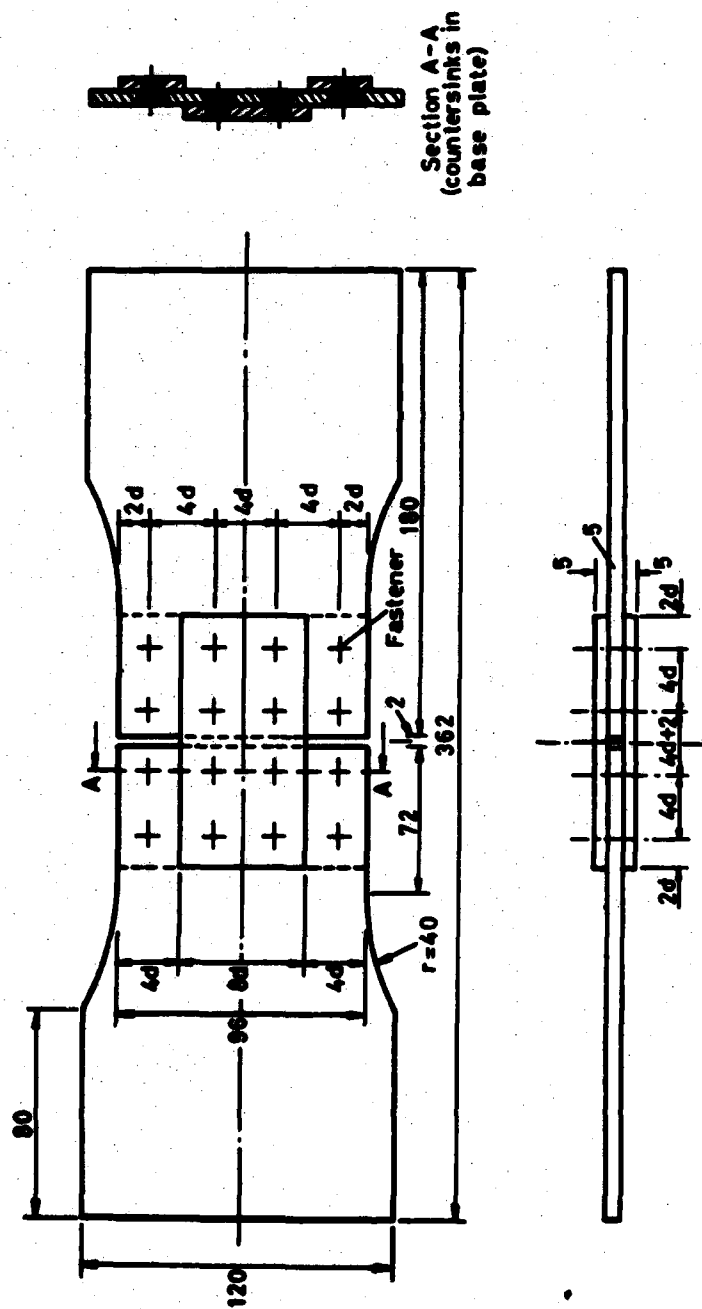


Fig 4 Swedish 'X' joint

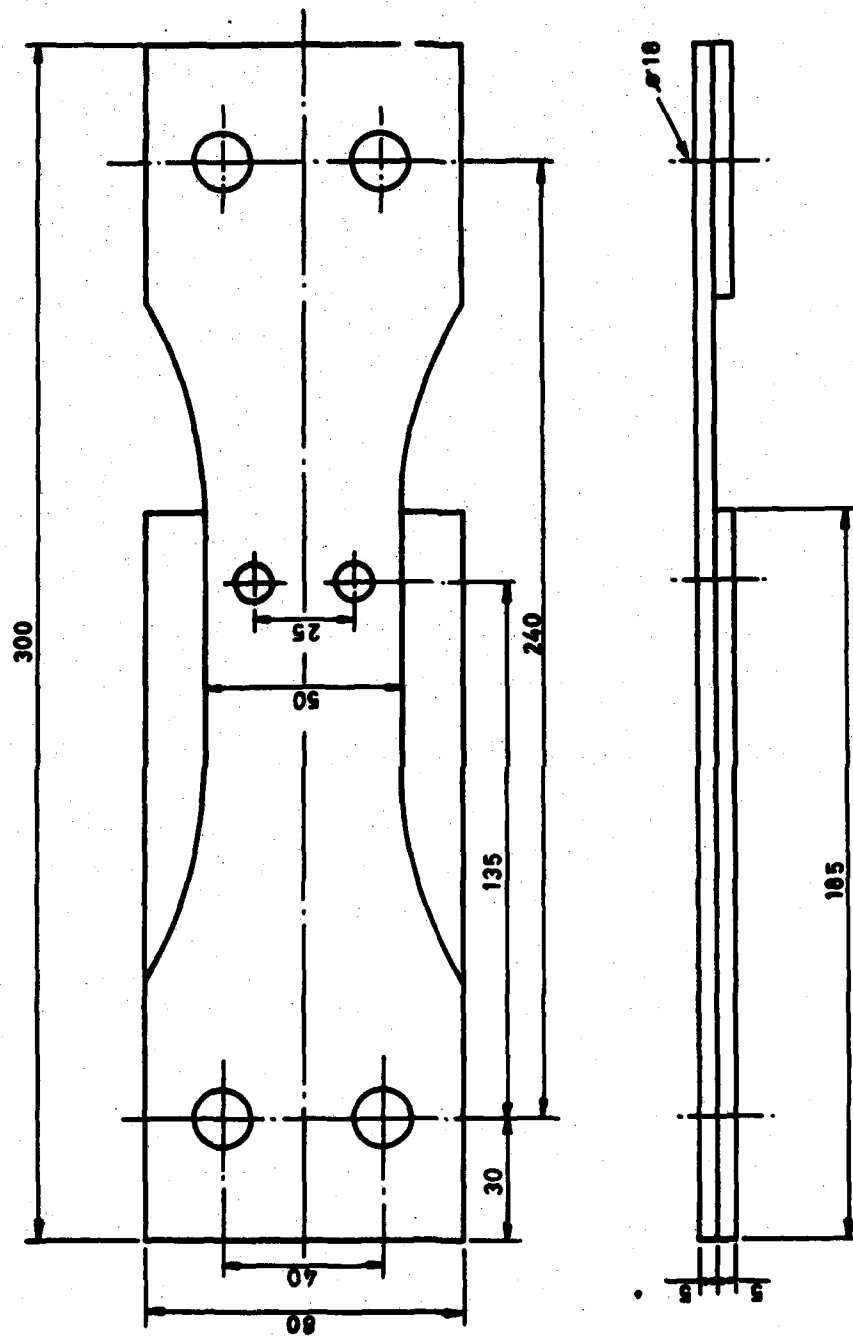


Fig 5 1½ dogbone specimen

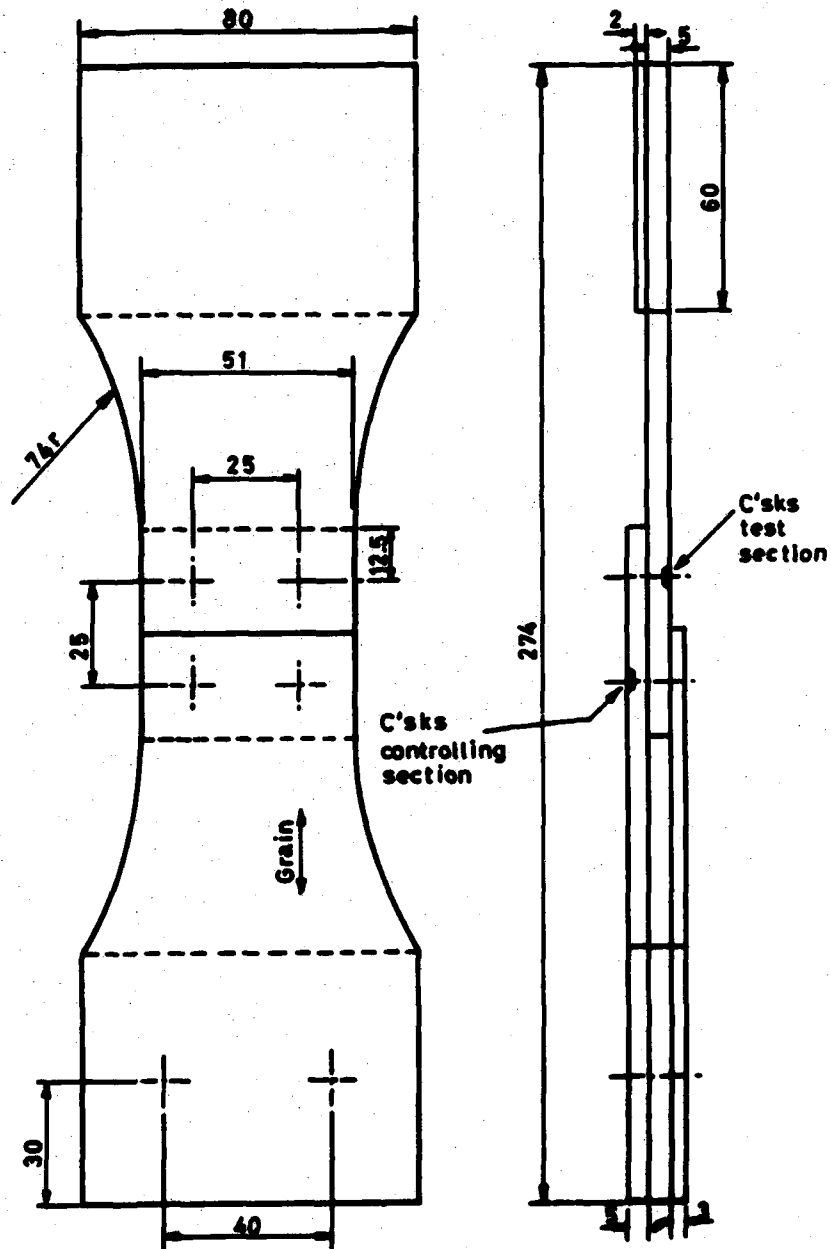
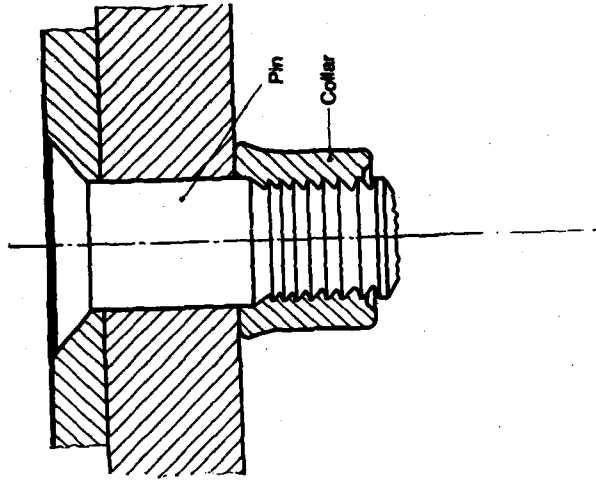


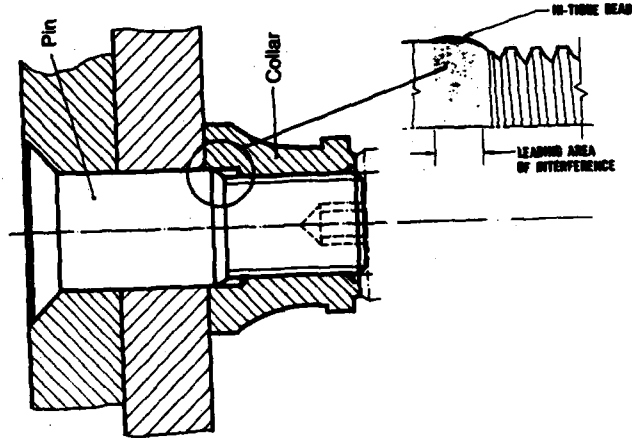
Fig 6 UK 'Q' joint



GPL Lockbolt fastener with flush head



Hi-Tigue fastener with flush head



Hi-Lok fastener with flush head

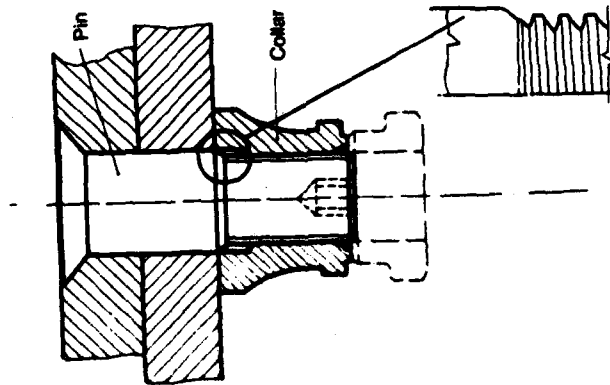


Fig 8 Fastener systems

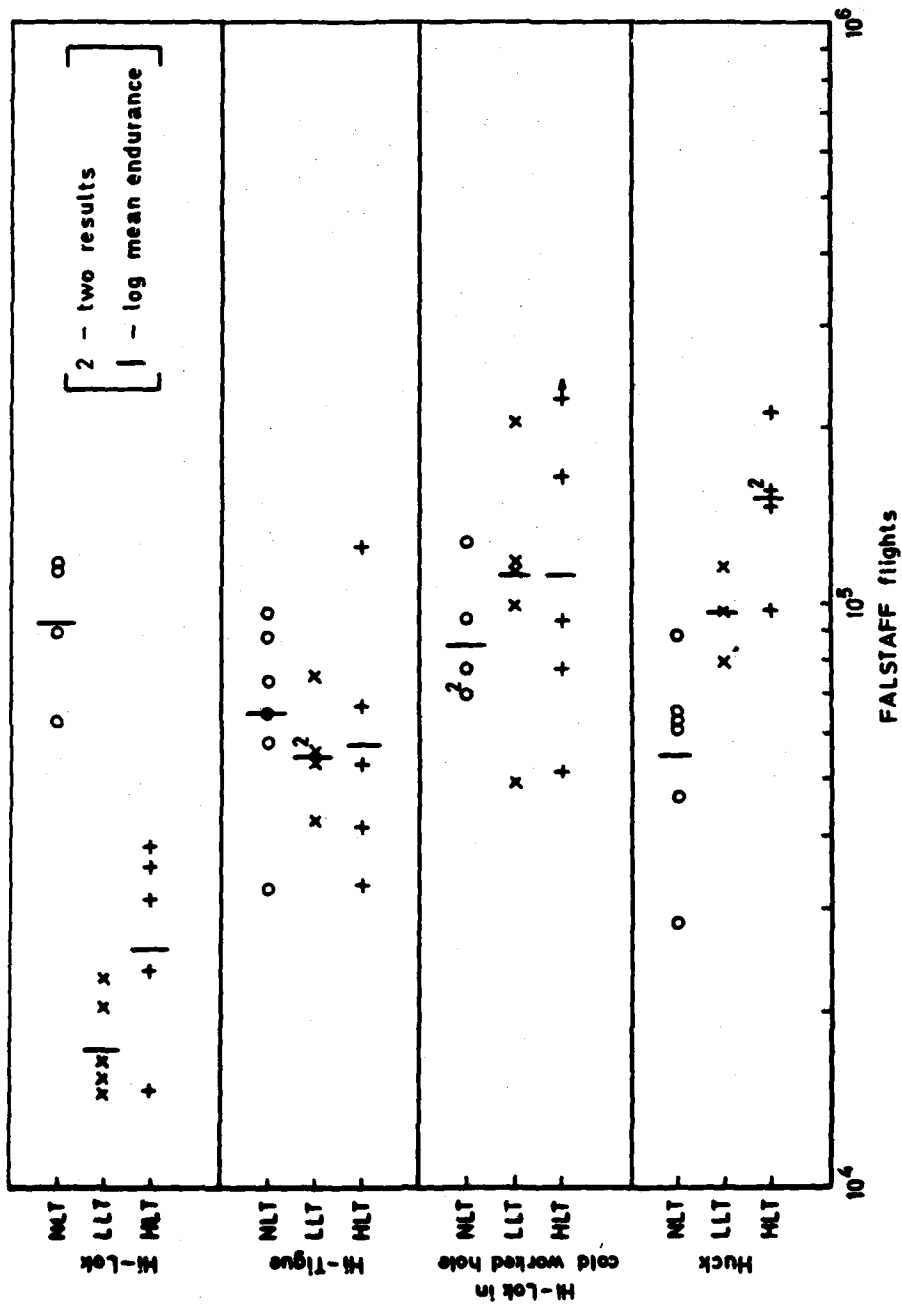
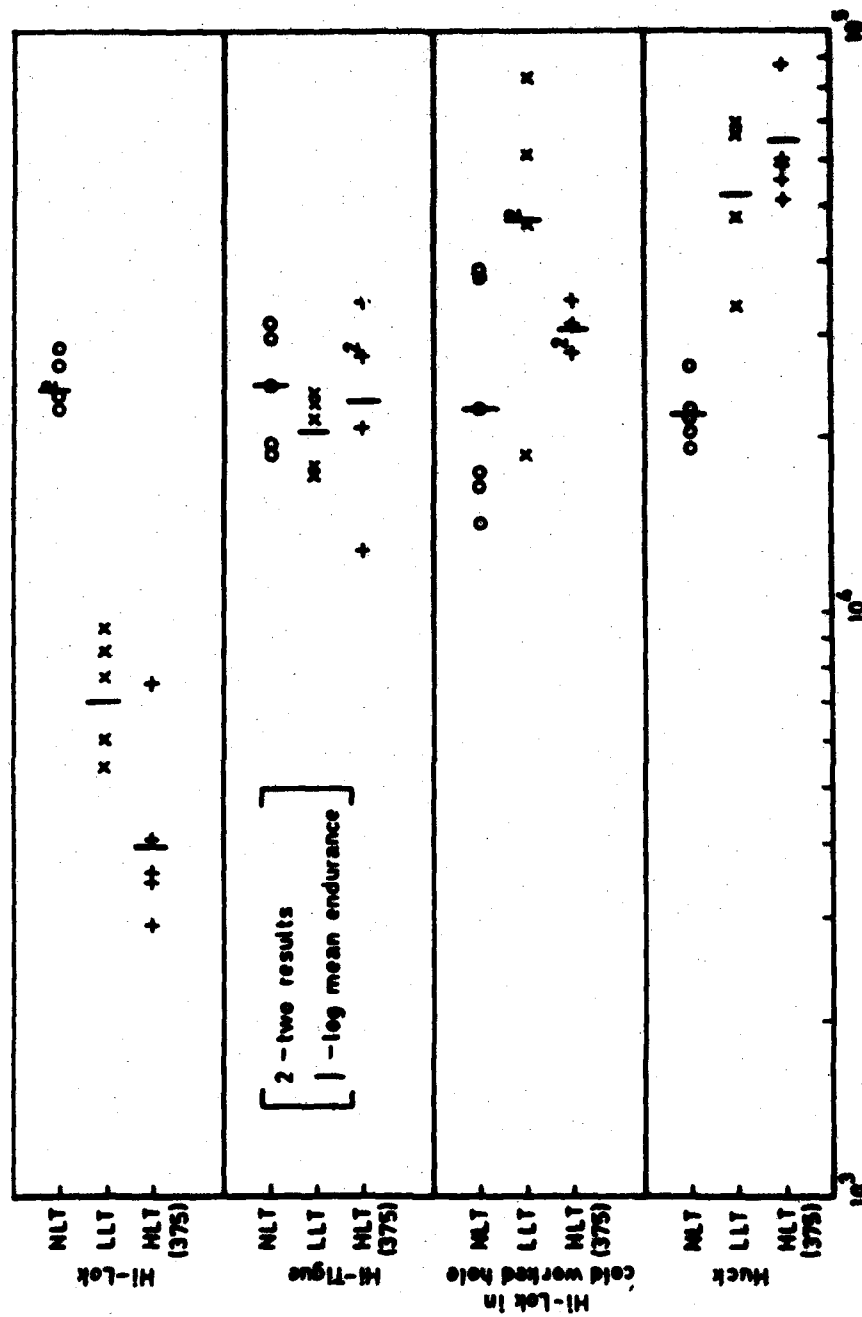


Fig 9 Fatigue endurance at 280MPa net section stress



FALSTAFF flights

Fig 10 Fatigue endurance at 350 MPa net section stress

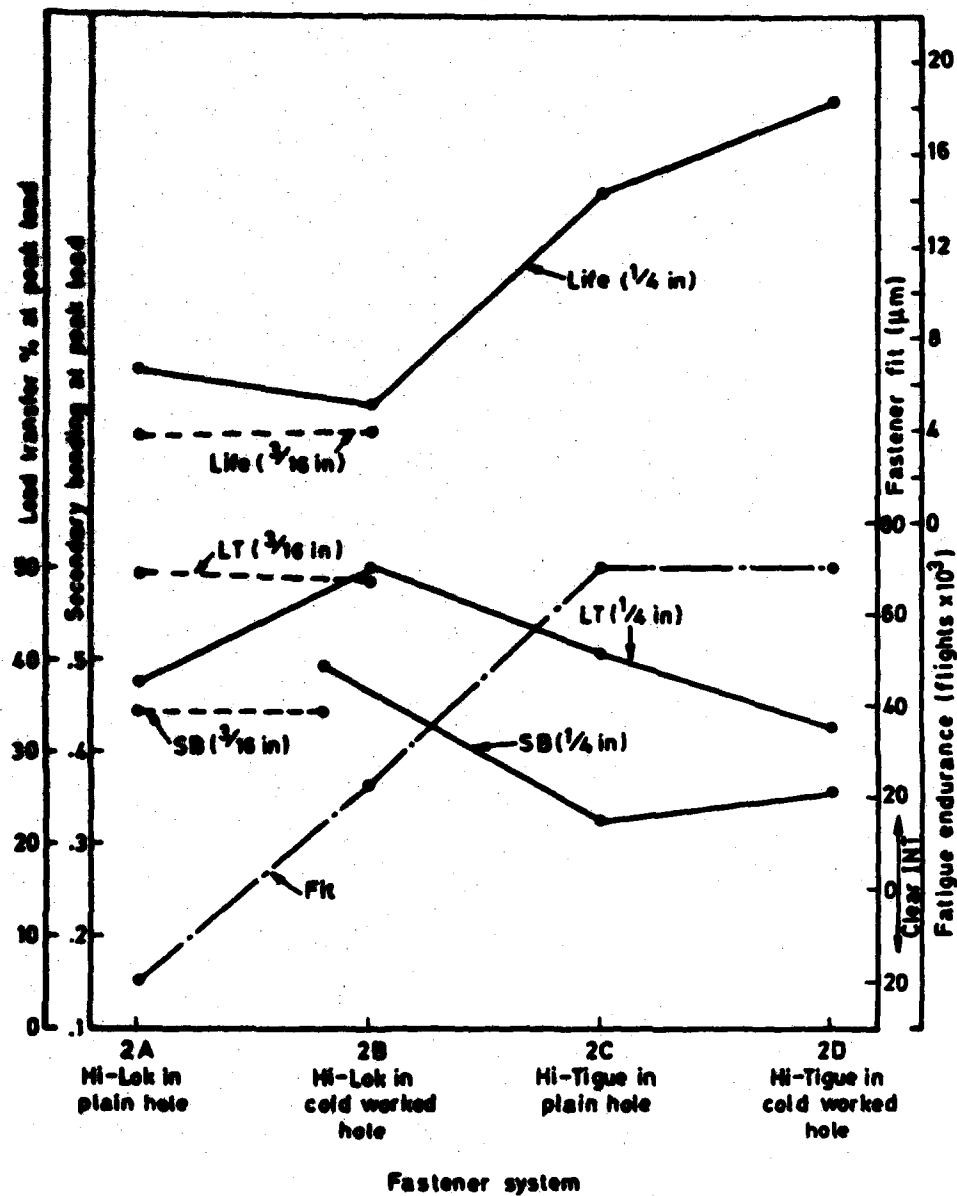


Fig 11 Summary of Q-joint data at 350MPa peak stress

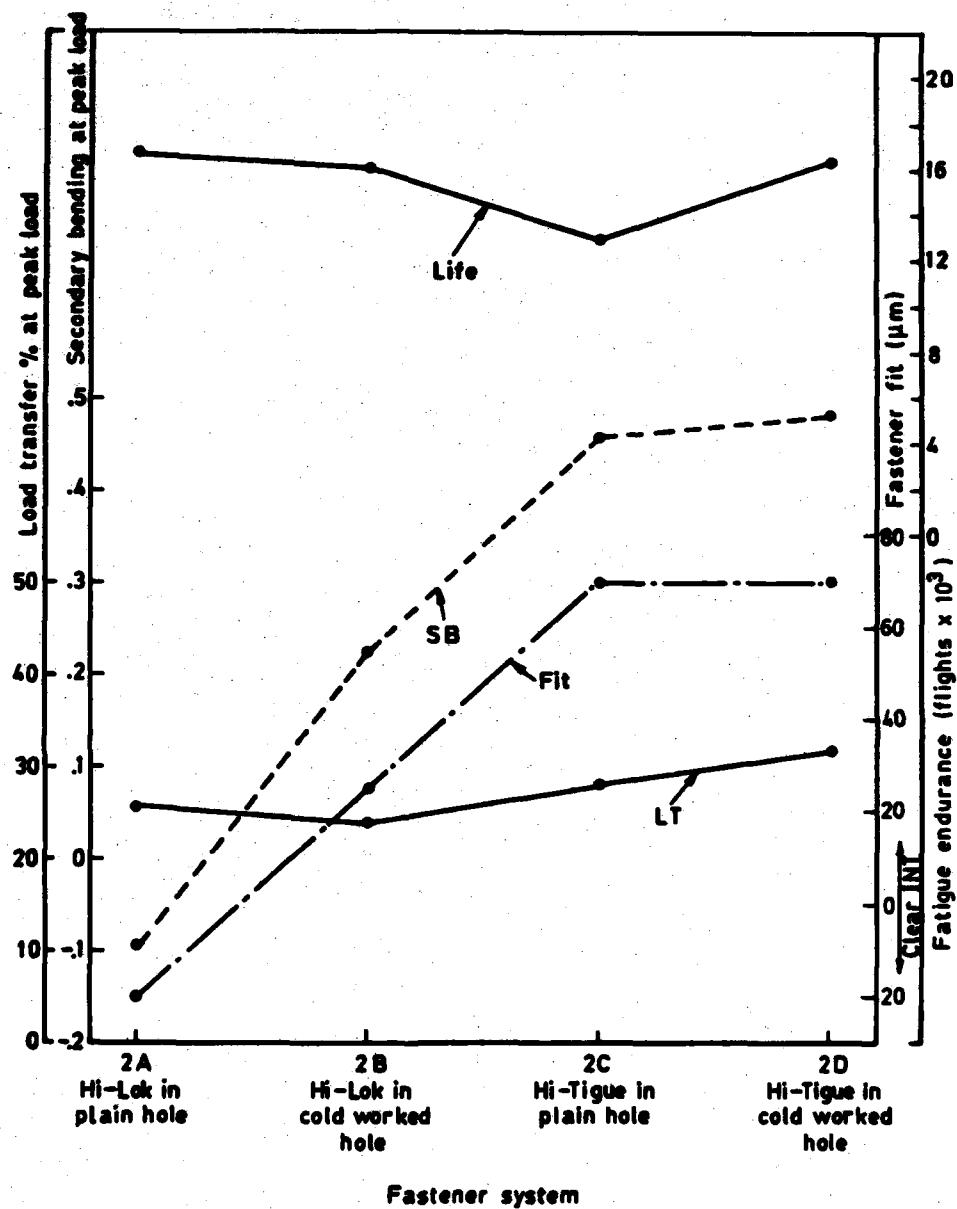


Fig 12 Summary of 1 $\frac{1}{2}$  dogbone data at 335MPa peak stress

## ANNEX 1

## FASTENER FITS

**A Fastener fits of no or low secondary bending joints**

In order to cover a range of fastener fits commonly used in practice, four ranges were chosen, two in combination with cold working. The four ranges chosen were:-

1A clearance	$20 \pm 10 \mu\text{m}$
1B interference	$25 \pm 10 \mu\text{m}$ (with cold work)
1C interference	$110 \pm 10 \mu\text{m}$
1D interference	$120 \pm 10 \mu\text{m}$ (with cold work)

In order to check these fits, both hole and fastener diameters were measured. The fasteners used were all from a common batch and the diameter variation was very low. The specimens were produced by the same manufacturer and the tolerances on hole diameter were found to be good, with the exception of system 1D where the hole was produced by a special tool. The specified and measured fits are given below for the four fastener systems.

1A	Range specified	$+10 + 30 \mu\text{m}$
	Hole diameter range	6.363 — 6.368 mm
	Fastener diameter range	6.325 — 6.337 mm
	Measured fit range	$+26 + 43 \mu\text{m}$
1B	Range specified	$-15 - 35 \mu\text{m}$
	Hole diameter range	6.312 — 6.317 mm
	Fastener diameter range	6.325 — 6.337 mm
	Measured fit range	$-8 - 25 \mu\text{m}$
1C	Range specified	$-100 - 120 \mu\text{m}$
	Hole diameter range	6.218 — 6.223 mm
	Fastener diameter range	6.325 — 6.337 mm
	Measured fit range	$-102 - 119 \mu\text{m}$
1D	Range specified	$-110 - 130 \mu\text{m}$
	Hole diameter range	6.198 — 6.248 mm
	Fastener diameter range	6.338 — 6.348 mm
	Measured fit range	$-90 - 150 \mu\text{m}$

**B Fastener fits of high secondary bending joints**

In order to cover a range of fastener fits commonly used in practice, four ranges were chosen, two in combination with cold working. The four ranges chosen were:-

2A clearance	$20 \pm 10 \mu\text{m}$
2B interference	$25 \pm 10 \mu\text{m}$ (with cold work)
2C interference	$70 \pm 10 \mu\text{m}$
2D interference	$70 \pm 10 \mu\text{m}$ (with cold work)

In order to check these fits, both the fastener diameter and hole diameters were measured. The HI-LOK fasteners used by each participant in systems 2A and 2B were not from a common batch, hence the measured fastener diameters are not necessarily consistent. The HI-TIGUE fasteners however were from a common batch and the measured diameters are therefore the same. Variation in fastener diameter for a given batch was found to be very low, usually less than about  $5 \mu\text{m}$ . The hole diameters produced and measured by individual participants also show good repeatability, generally within  $15 \mu\text{m}$ . All hole diameters were measured, and a summary of measurements and fits is given below.

**Fastener system 2A — (range specified  $+10 + 30 \mu\text{m}$ )**

Joint	Hole dia. range (mm)	Fastener dia. (mm)	Range of fits ( $\mu\text{m}$ )
Q	6.363 — 6.368	6.330	$+33 + 38$
U	6.315 — 6.320	6.324	$-4 - 9$
1 1/2	6.331 — 6.341	6.310	$+21 + 31$
X	6.345 — 6.360	6.330	$+15 + 27$

**Fastener system 2B — (range specified  $-15 - 35 \mu\text{m}$ )**

Joint	Hole dia. range (mm)	Fastener dia. (mm)	Range of fits ( $\mu\text{m}$ )
Q	6.312 — 6.317	6.330	$-16 - 21$
U	6.320 — 6.327	6.324	$+3 - 4$
1 1/2			
X	6.325 — 6.339	6.330	$+9 - 5$

Fastener system 2C — (range specified —60 —80  $\mu\text{m}$ )

$\frac{Q}{1\frac{1}{2}} \left. \begin{array}{l} \\ U \end{array} \right\}^{\circ}$	6.246—6.258	6.325	—67—79
	6.225—6.250	6.325	—75—100

Fastener system 2D (range specified —60 —80  $\mu\text{m}$ )

$\frac{Q}{1\frac{1}{2}} \left. \begin{array}{l} \\ U \end{array} \right\}^{\circ}$	6.246—6.257	6.325	—68—79
	6.220—6.235	6.325	—90—105

\*Holes produced by the same reamer

## ANNEX 2

## PIN, COLLAR AND NUT PART NUMBERS USED IN INVESTIGATION

This annex gives the pin and collar/nut part numbers used throughout the investigation.

## Fastener system 1A and 1B

NLT joint	HL19PB-8-6	with	H604-4 nut
LLT joint	HL11VAP-8-8	with	H604-4 nut
HLT joint	HL19PB-8-11	with	H604-4 nut

## Fastener system 1C

NLT joint	HLT319-8-6	with	H541L-4F nut
LLT joint	HLT411AF-8-8	with	H541L-4F nut
HLT joint	HLT319-8-11	with	H541L-4F nut

## Fastener system 1D

*1 NLT joint	GFL3SC-DT08-08AC	with	2SCC-3C08 collar
LLT joint	GFL3SC-V08-08AC	with	2SC-3C08 collar
HLT joint	GFL3SC-DT08-11AC	with	2SCC-3C08 collar

## Fastener system 2A and 2B

Q joint	HL19PB-8-7	with	HL70-8 collar
	& HL19PB-6-9	with	HL70-6 collar
1 1/2 dogbone	HL19PB-8-7	with	HL70-8 collar
U joint	HL19PB-8-7	with	HL70-8 collar
*2 X joint	HL19PB-8-7	with	HL70-8 collar

## Fastener system 2C and 2D

Q joint	HLT319-8-7	with	H541L-4F nut
	& HLT319-8-9		
1 1/2 dogbone	HLT319-8-7	with	H541L-4F nut
U joint	HLT319-8-7	with	H541L-4F nut

\*1 These fasteners were not available in the -6 grip length. The -8 grip length was used with a 7 mm thick washer.

\*2 Joints are assembled with a 1 mm thick washer.

## ANNEX 3

## LOAD TRANSFER AND SECONDARY BENDING MEASUREMENTS

The method adopted for measuring load transfer and secondary bending in joints was that used in the FRFS programme. Strain gauges were attached to the specimens at various locations as described in Annex 4 of reference 2. The SB gauges were attached on either side of the failing element near to the fasteners from which failure occurs. The SB ratio was simply calculated as the ratio of the bending strain to the axial strain. The LT gauges were attached to either side of the specimen at two distinct locations. One location was remote from the test section and measured the total load applied. The other location was on the failing element beyond the row of fasteners from which the failure occurred. This row of gauges measured the load bypassing the fasteners. The method of averaging these values was not defined. The method used on the Q-joint consisted of averaging consecutive values across the section. The method used on the 1 1/2 dogbone consisted of integrating a fifth order polynomial fit obtained from the surface strain measurements. Each method was used consistently and comparisons should only be made of LT values on each specimen with different fastener installations. Comparisons between LT values for different joints should only be used as a guide.

Values of LT and SB are dependent on the applied load. Accordingly measurements from the strain gauges were taken over the range of loads which were applied during the fatigue tests. The range was split into discrete levels and measurements were taken at each level given below.

% of maximum load  
in FALSTAFF

0  
16.7  
33.3  
50  
66.7  
83.3  
100  
83.3  
66.7  
50  
33.3  
16.7  
0

minimum load  
0

The LT and SB values were calculated at each discrete level for each strain gauge pair. The average value was calculated across the section and is presented in tabular form. The data also shows how the LT and SB values vary throughout a loading cycle. A measurement cycle was made at the start of the test. In order to ensure that measurements were also available when the joint was stabilised, a bedding-in procedure was used. This simply involved cycling the joint from zero load to 50% of the maximum FALSTAFF load for a number of cycles. The measurement cycle was then repeated. This process was repeated until the measurements of LT and SB had stabilised. The loading sequence used in this programme is given below:-

- 0 - 100% FALSTAFF - MIN FALSTAFF - 0
- 0 - 50% FALSTAFF - 0 (5000 CYCLES)
- 0 - 100% FALSTAFF - MIN FALSTAFF - 0
- 0 - 50% FALSTAFF - 0 (5000 CYCLES)
- 0 - 100% FALSTAFF - MIN FALSTAFF - 0

The \* represents the measurement cycle described earlier.

The complete FALSTAFF load range was not used for the bedding-in process. This is because experience showed a high percentage of strain gauge failures using the complete sequence. Since some of the gauges were adhered to the faying surfaces, replacement was difficult and time consuming. The compromise bedding-in process however resulted in some strain gauge hysteresis, during the measurement cycle. The measurements of LT and SB presented in this report are those obtained after the bedding-in procedure.

## ANNEX 4

## IMPORTANCE OF SCATTER

The fatigue endurance for the no or low secondary bending programme are presented in figures 9 and 10 for the case of low and high applied stresses respectively. The scatter is generally lower at the higher stress level but not significantly. There appears to be no relationship between fastener system and the amount of scatter. The NLT transfer specimen endurance are similar with all of the fastener systems and at both stress levels and are therefore not further considered in this Annex.

The fatigue life scatter bands of the three enhanced fastener systems (1B, 1C and 1D) overlap for both joints at both stress levels. It should be borne in mind that the HLT joint endurance were obtained at 375MPa and the LLT joint at 350MPa. Scatter bands of the datum fastener system only overlap those of the other three systems in one case. This is the case of the HLT joint at the lower stress level with HI-TIGUE fasteners. This could potentially result in a lower than unity life improvement with HI-TIGUE fasteners over the datum system.

To quantify the effects of scatter on fatigue life improvement factors (LIF), the results are analysed in two ways. Firstly the extremes of LIF are calculated from the data. Secondly each data set is considered to be distributed in some regular way. The minimum lives of each data set are used to calculate LIF (min) and the maximum lives of each data set to calculate LIF (max). Assuming the distribution of each data set to be log normal, the log mean values are also used to calculate a factor LIF (Av).

TABLE A1 Absolute Life Improvement Factors

FASTENER SYSTEM	LLT JOINT		HLT JOINT	
	280MPa	350MPa	280MPa	375MPa
HI-TIGUE	1.86 - 5.22	1.85 - 4.31	0.86 - 8.31	1.71 - 11.57
HI-LOK IN C.W. HOLE	2.17 - 14.24	2.03 - 15.41	1.35 - 15.14	3.61 - 11.67
HUCK EXL IN C.W. HOLE	3.53 - 8.03	3.62 - 12.83	2.56 - 14.28	7.00 - 29.57

TABLE A2 Distributed Life Improvement Factors

FASTENER SYSTEM	LIF	LLT JOINT		HLT JOINT	
		280	350	280	375
HI-TIGUE	MIN	2.94	3.15	2.21	4.38
	AV	3.14	2.81	2.10	4.54
	MAX	3.30	2.53	3.25	4.52
HI-LOK IN C.W. HOLE	MIN	3.44	3.46	3.45	9.25
	AV	6.05	6.36	3.96	6.41
	MAX	8.99	9.05	5.92	4.56
HUCK EXL IN C.W. HOLE	MIN	5.58	6.16	6.54	17.90
	AV	5.48	7.18	5.53	11.99
	MAX	5.07	7.53	5.59	11.56

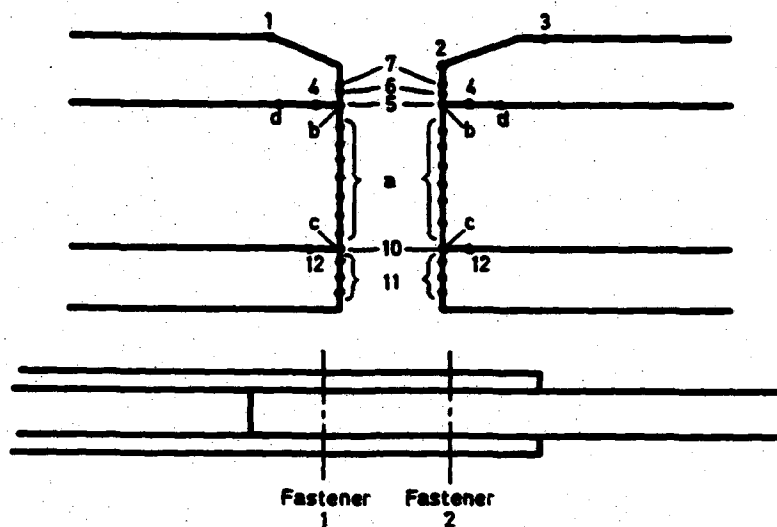
From these two tables it can be seen that there are no systematic differences in the way in which the two types of joint rate the fastener systems. It does however indicate that the life improvement factor based on the log mean values (Table A2) of the endurance data provide a good guide to the improvements found in practice. If worst case data is required for minimum life improvement estimations, then the absolute approach (Table A1) must be used.

## ANNEX 5

## PRIMARY FATIGUE CRACK ORIGINS

Primary fatigue crack origins have been noted by each participant on each fatigue test specimen and are presented in this annex.

## a) HLT Specimen



FASTENER SYSTEM	Maximum net Stress (MPa)	SPEC NO	Flights to Failure	ORIGINS
1A. HI-LOK IN PLAIN HOLE	280	H1/1	37898	4
	280	H1/6	23172	10
	280	H1/5	30839	a
	280	H1/10	34929	c
	280	H1/7	14821	10
	375	H1/2	7572	a
	375	H1/9	4031	a
	375	H1/8	3559	a
	375	H1/3	3431	a
	375	H1/4	2959	5,6,7,11

Fastener system	Maximum net Stress (MPa)	SPEC NO	Flights to Failure	ORIGINS
1B. HI-TIGUE IN PLAIN HOLE	280	H4/2	66624	-
	280	H4/5	32796	b
	280	H4/7	52172	10
	280	H4/9	123227	6,7
	280	H4/10	41024	b
	375	H4/1	34224	10
	375	H4/3	27749	10
	375	H4/4	27031	10
	375	H4/6	12972	6,7
	375	H4/8	20924	6,7
1C. HI-LOK IN COLD-WORKED HOLE	280	H6/2	51172	11
	280	H6/8	76759	11
	280	H6/4	> 224420	-
	280	H6/1	166196	11
	280	H6/9	93021	11
	375	H6/7	31759	11
	375	H6/3	34525	11
	375	H6/6	27772	5
	375	H6/10	27359	6,7
1D. HUCK-EXL IN COLD-WORKED HOLE	280	H3/9	211711	d,12
	280	H3/1	155031	b
	280	H3/3	155172	b
	280	H3/4	96996	d
	280	H3/5	146572	d
	375	H3/6	87511	b
	375	H3/7	58880	10
	375	H3/8	55172	c
	375	H3/10	59929	b
	375	H3/2	52972	10

Summary of HLT-joints

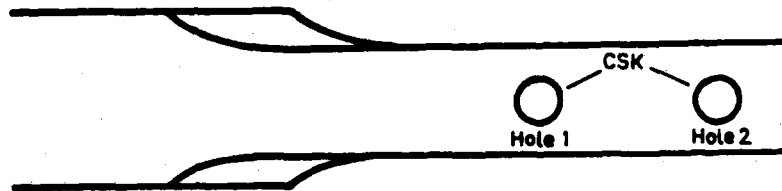
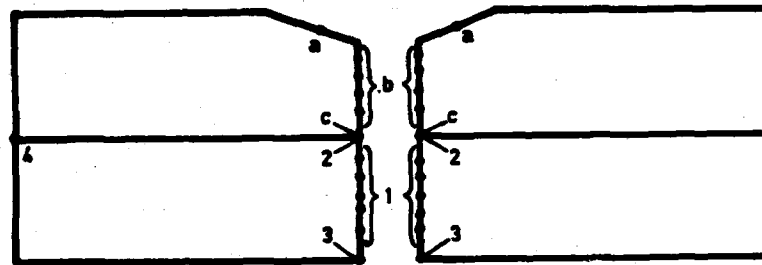
Fastener System	TOP PLATE (CSK)		BOT PLATE		CENTRE PLATE	
	280	375	280	375	280	375
1A	(1) 37898	(4) 2959	(6) 23172 (7) 14821		(5) 30839 (10) 34929	(2) 7572 (9) 4031 (8) 3559 (3) 3431
	37,898	2,958	18,532		32,820	4,394
1B	(9) 123227	(6) 12972 (8) 20924	(7) 52172	(1) 34224 (3) 27749 (4) 27031	(5) 32796 (10) 41024	
	123,227	16,475	52,172	28,396	36,680	
1C		(6) 27772 (10) 27359	(2) 51172 (8) 76759 (1) 166196 (9) 93021	(7) 31759 (3) 34525		
		27,565	88,276	33,113		
1D			(9) 211711	(7) 58880 (2) 52972	(9) 211711 (1) 155031 (3) 155172 (4) 96996 (5) 146572	(6) (8) (10)
			211,711	55,848	148,579	66,141

( ) Specimen numbers

## Observations

- (1) Failures in the top and bottom plates originate at fastener 1.
- (2) Failures in the centre plate originate at fastener 2.
- (3) The majority of failures using system 1D are in the centre plate, the longest lives are achieved with this system.
- (4) All of the failures using system 1C are in the side plates, the majority in the bottom plate.
- (5) The majority of failures using system 1B are in the side plates.

## b) LLT Specimen



Fastener System	Maximum net Stress (MPa)	SPEC NO	Flights to Failure	ORIGINS
1A. HI-LOK IN PLAIN HOLE	280	166	15372	(1) b
	280	167	14329	(2) b
	280	168	20172	(2) b
	280	169	22680	(1) c, b, 1
	280	170	16572	(1) c, b, 1
	350	161	6031	(2) b
	350	162	7772	(1) b, 1
	350	163	5424	(1) c (2) 1
	350	164	9239	(2) b, 1
	350	165	8572	(1) 1 (2) b
1B. HI-TIGUE IN PLAIN HOLE	280	L4/1	55351	(2) a
	280	L4/9	54772	(1) a
	280	L4/4	53172	(1) 2 (2) a
	280	L4/7	42172	(1) a
	280	L4/10	74772	(2) a (1) a
	350	L4/6	17080	(1) a
	350	L4/3	17729	(2) a
	350	L4/8	22959	(1) a
	350	L4/5	21572	(1) 2 (1) a
	350	L4/2	23372	(1) a

Fastener System	Maximum net Stress (MPa)	SPEC NO	Flights to Failure	ORIGINS
1C. HI-LOK IN COLD-WORKED HOLE	280	186	49231	(1) 2,1
	280	187	118194	(2) b,2
	280	189	115231	(2) b,2
	280	190	99031	(1) 3,1
	350	181	18759	(1) 1,2
	350	182	61325	(1) b,1
	350	183	46586	(1) 4,1
	350	185	83591	(1) 1,3
1D. HUCK-EXL IN COLD-WORKED HOLE	280	196	79972	(2) 1
	280	198	115021	(2) c, b
	280	200	97031	(2) a
	350	191	69611	(1) 2
	350	193	66231	(1) a
	350	194	33431	(1) 2
	350	195	47943	(2) a, b

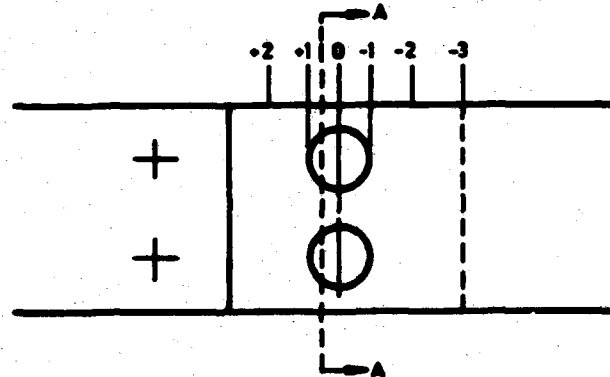
#### Observations of LLT joints

- (1) Failure from hole (1) was more common than from hole (2) (60% at (1) 40% at (2)) but in no systematic way.
- (2) Failure from the countersinks was observed only with high interference fit fasteners.
- (3) All of the failures with system 1B originated at the countersinks, only 50% with system 1D originated at the countersink.
- (4) All of the failures with fastener systems 1A and 1C originated from multiple origins at the bore of the hole.

50

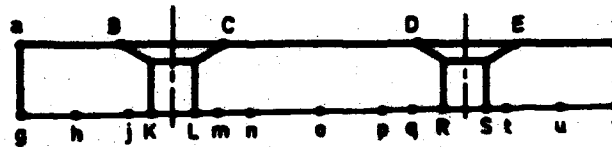
c) Q-joint

Position of  
failure section



AA

Failure  
section



Fastener system	Maximum net (Stress MPa)	SPEC NO	FLIGHTS TO FAILURE	ORIGINS
2A. HI-LOK IN PLAIN HOLE	280	X3	12128	(-1) j,m,q,t
	280	X4	14431	(-1) h,m,q,t
	280	X7	12160	(-1) m,q(0)S
	280	X9	13831	(-1) j,m,q,t
	280	X10	14031	(-1) j,q,t
	350	X1	3925	(-1) m,t
	350	X2	2929	(0) K,L,R,S
	350	X5	3444	(0) K,L,R,S
	350	X6	4336	(0) K,L,R,S

Fastener system	Maximum net Stress (MPa)	SPEC NO	FLIGHTS TO FAILURE	ORIGIN
2B. HI-LOK IN COLD WORKED HOLE	280	CW2	9631	(-2) g, (-1)
	280	CW4	14424	(-2) o, p
	280	CW6	12329	(-1.5) O(O)K
	280	CW9	16224	(-1.5) h, q, u
	280	CW10	17631	(-1) j, m, p, t, u
	350	CW3	3801	(0) K, L, q, S
	350	CW5	3172	(0) K, L, S
	350	CW7	3624	(0) K, L, R
	350	CW8	5323	(0) K, L, R, (-1) o, u
2C. HI-TIGUR IN PLAIN HOLE	280	12	78 032	(+1) B, (0), L
	280	13	25 225	(+1) E, (0), R
	280	14	30 860	(+1) B
	280	17	18 530	(+1) D, E
	280			
	350	15	15825	(+1) E
	350	16	21730	(-1) L, q
	350	19	11 173	(-3) u
	350	20	16 385	(-1) q, t
	350	21	8 232	(-1) n
	350	22	13 573	(+1) E
2D. HI-TIGUR IN COLD WORKED HOLE	280	4	25 573	(+2) a
	280	5	45 632	*1
	280	6	77 330	(+2) f(O)R
	280	7	111 393	*2
	280	10	91 225	(-1) v(O)R
	350	2	38 981	(-.5) p
	350	3	32 695	(-1) h
	350	8	16 840	(-3) u
	350	9	11 159	(-1) n
	350	11	7997	(-2) u

\*1 Failure from defect near end plate

\*2 Failure from fasteners in controlling section

#### O-Joint Summary

Fastener system/stress level - Failure site

2A/low - On -1 line, just away from edge of hole

2A/high - On 0 line, at edge of hole.

2B/low - On -1.5 line, well away from edge of hole

2B/high - On 0 line, at edge of hole.

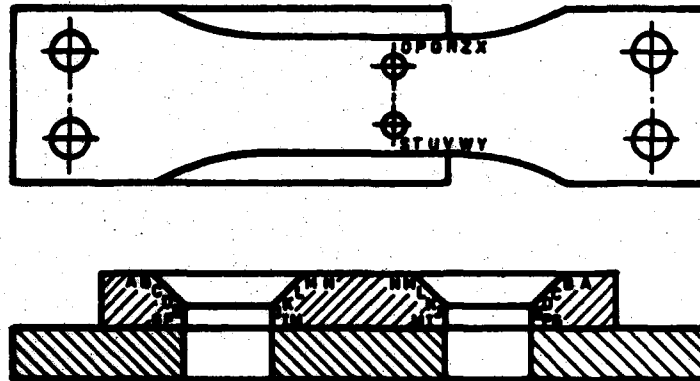
2C/low - On +1 line, at edge of counterbore

2C/high - On +1 line, at edge of counterbore or  
On -1 line, near edge of hole.

2D/low - Various - edge of specimen

2D/high - On -1.5 line, well away from edge of hole.

d) 1 1/2 Dogbone



Fastener system	Maximum net Stress (MPa)	SPEC NO	FLIGHTS TO FAILURE	ORIGIN
2A. HI-LOK IN PLAIN HOLE	268		18411	S
	268		60372	R
	268		56972	S
	268		63831	E
	335		9559	F
	335		15419	S
	335		23373	F
	335		22231	E
2B. HI-LOK IN COLD WORKED HOLE	268		29572	S
	268		40431	R → W
	268		58231	S
	268		35759	R → V
	335		13524	R → V
	335		14231	R
	335		17962	P → T
	335		19172	G
2C. HI-TIGUE IN PLAIN HOLE	268	C1	30764	G
	268	C5	36572	H
	335	C4	9983	G
	335	C2	16734	U
	335	C3	14067	U
	335	C8	11780	G
2D. HI-TIGUE IN COLD WORKED HOLE	268	D1	37146	A
	268	D2	42640	Y
	268	D6	28265	Q
	335	D7	19007	P
	335	D5	17308	P
	335	D8	14946	B
	335	D3	14564	T
2A. HI-LOK IN PLAIN HOLE (COMPATABILITY)	335	A3	11165	F
	335	A1	13826	E
	335	A2	19955	G

## 1 1/2 Dogbone Summary

## Fastener system/stress level — Failure site

2A/low — From edge of hole at interface or just forward of hole.

2A/high — From edge of hole at interface or just forward of hole.

2B/low — Just forward of hole or at edge of side plate.

2B/high — At edge of side plate or from edge of hole at interface.

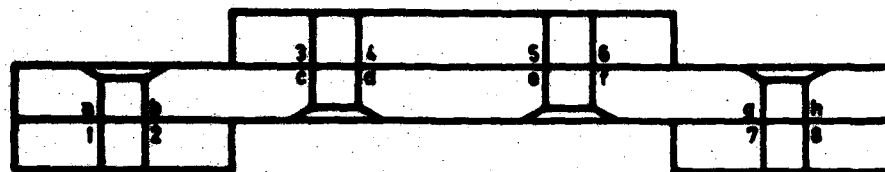
2C/low — Just away from edge of hole at interface

2C/high — Just away from edge of hole at interface or forward of fastener holes.

2D/low — Various — away from fastener hole on top surface.

2D/high — Just forward of fastener hole on top surface.

e) X-joint



Fastener system	Maximum net Stress (MPa)	SPEC NO	FLIGHTS TO FAILURE	ORIGIN
2A. HI-LOK IN PLAIN HOLE	200	41.6	13860	1-6
	200	41.7	16972	a,b,d-h
	200	41.8	13180	a-e,g
	200	41.2	13772	a-f
	267	41.1	5425	a-f,h
	267	41.3	5329	a-h
	267	41.4	5590	a-f
	267	41.5	6280	a,c-h
2B. HI-LOK IN COLD WORKED HOLE	200	42.4	42772	1-6,h
	200	42.5	30224	1-8
	200	42.6	35631	1-8
	200	42.8	27630	1,3-6,8
	267	42.1	10929	a-h
	267	42.2	11972	a-h
	267	42.3	11372	a,c-h
	267	42.7	6172	1-8

## X-joint Summary

Fastener system/stress level — Failure site

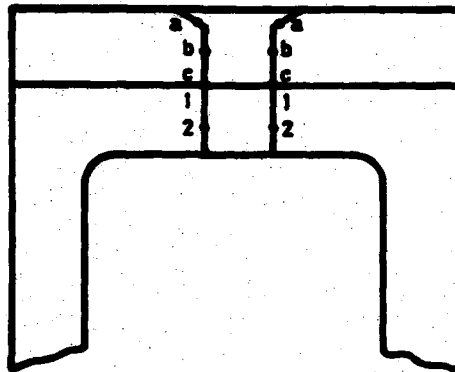
2A/low — from fastener holes in base plate

2A/high — from fastener holes in base plate

2B/low — from fastener holes in splice plate

2B/high — from fastener holes in base plate

## 9) U-joint



Fastener system	Maximum net Stress (MPa)	SPEC NO	FLIGHTS TO FAILURE	ORIGIN
2A. HI-LOK IN PLAIN HOLE	276	S1-4	7831	b,c
	276	S1-5	19311	2
	276	S1-6	10631	1,2
	276	S1-7	23631	b,c
	345	S1-1	5558	1,2
	345	S1-2	5729	a,c
	345	S1-3	5431	b
	276	S3-4	24372	1,2
	276	S3-5	17834	1,2
2C. HI-TIGUE IN PLAIN HOLE	276	S3-6	16031	1,2
	276	S3-7	19572	1,2
	345	S3-1	15424	a
	345	S3-2	13520	2
	345	S3-3	13969	1,2

## ANNEX 6

## Q-JOINT ASSESSMENT

The Q-joint has been developed during the past three years. It is anticipated that development will continue to enable the joint to produce different amounts of LT and SB by simple geometric changes. These changes involve fastener diameter, thickness of controlling element and spacing of fastener rows. The standard Q-joint design is given in Fig. 3 with 1/4" diameter fasteners installed. Testing of the Q-joint with HI-LOK (2A) and HI-LOK in a cold worked hole (2B), was performed with 3/16" diameter fasteners installed in the controlling section, and 1/4" diameter fasteners in the test section. In order to assess whether using the standard joint would produce similar fatigue lives to those obtained with the smaller fastener in the controlling section, measurements of LT and SB were made on standard joints. The results of these measurements are given in table 4, and are compared with those obtained using the smaller 3/16" diameter fastener, presented in table 5. Many strain gauge failures occurred during the testing of the 1/4" standard joint, particularly with the plain hole specimen. Comparisons can however be made of the cold worked specimens. The load transfer values are very similar but the secondary bending is somewhat higher in the standard joint over most of the load range. It is expected therefore that the fatigue lives of standard Q-joints with 1/4" HI-LOK fasteners in plain and cold worked holes will be slightly shorter than those with 3/16" diameter fasteners in the controlling section. A small number of tests have been performed with the standard joint, and the above appears to be true at the lower stress level. At the higher stress level however the fatigue endurances with the standard joint are slightly greater than those with the 3/16" fasteners. Since the secondary bending is so high, it is expected that there would be little difference between the fatigue lives of plain and cold worked hole specimens. This also appears to be true from the small number of additional tests.

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